# IMITATIVE RESEARCH AND DEVELOPMENT IN THE NEO-SCHUMPETERIAN THEORY OF GROWTH

By

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This dissertation explores endogenous technology transfer through imitation. The context is a dynamic general equilibrium model of growth generated by innovation. Segerstrom extends the one-factor quality ladders model of Grossman and Helpman by incorporating endogenous imitation. Comparative static experiments produce perverse results. An increase in a subsidy to innovative (or imitative) activity *reduces* the level of innovative (or imitative) activity. In Chapter 2, I show that Segerstrom's model is unstable because of linear research and development (R&D) unit costs. This instability causes the perverse results.

By introducing specific factors to innovation and imitation, I obtain instantaneous diminishing returns to R&D technology at the aggregate level, while still allowing for constant returns to scale at the firm level. I then derive sufficient conditions for stability requiring a certain level of instantaneous diminishing returns to R&D activity. The

satisfaction of these conditions assures the 'usual' comparative static results of subsidies to either type of R&D: an increase in a subsidy to innovative (or imitative) activity *increases* innovative (or imitative) R&D activity.

In Chapter 3, I develop a one-factor general equilibrium model of global growth. I analyze trade among advanced countries in a two-country, integrated equilibrium, world economy. Risky and costly imitation is the only channel of technology transfer across countries. The patterns of trade and technology transfer fluctuate stochastically in each industry and exhibit product cycles and endogenous two-way international technology transfer. These trade and transfer patterns depend on relative national labor endowments.

I investigate the relevance of knowledge spillovers for theory and policy in Chapter 4, and examine the struggle of recent empirical efforts to measure the magnitude and extent of spillovers. These studies do not distinguish between research efforts aimed primarily at incremental improvements (or imitation) and R&D directed at being first to bring out the next major product line (or innovation). As a result, they may produce biased estimates of spillovers from foreign R&D. I argue that intraindustry technology (or knowledge) transfers are aggressively acquired rather than passively 'spilled.'

# CHAPTER 1
# IMITATION IN GROWTH AND TRADE

## 1.1 Introduction

> *[I]f we can learn about government policy options that have even small effects on the long-term growth rate, then we can contribute much more to improvements in standards of living than has been provided by the entire history of macroeconomic analysis of countercyclical policy and fine-tuning. Economic growth ... is the part of macroeconomics that really matters.*
>
> *Barro and Sala-i-Martin (1995, p.5)*

Nature moves inexorably forward, renewing, refining, replacing--so does humanity. From the first rudimentary scraping knifes and the taming of fire to the Hubble telescope and the splitting of the atom, we never cease our search for a better way to get what we want, or more of it. We have more and better things every year. In the language of economics, this is growth. It has been a staple of economic study since the days of Adam Smith. This field, dominated by Neoclassical growth theory for years, is enjoying a current renaissance, the focus shifting from analyzing capital accumulation to understanding technological change.

The Neoclassical theory of growth is based on the Solow (1956) - Swan (1956) neoclassical production function model, as integrated with Ramsey's (1928) treatment of

household optimization by Cass (1965) - Koopmans (1965).[1] It predicts a per-capita growth rate that converges, in the long run, to an exogenous rate of technical change. Neoclassical growth theory provides the comforting assertion (to the Neoclassical economists) that the competitive outcome is Pareto optimal. In fact, there is no government policy tool that would increase the long-run growth rate in the Neoclassical model. The Neoclassical theory also explains several empirical stylized facts, including per-capita output growing over time, physical capital per worker growing over time, and conditional convergence in growth rates of output (conditional on such factors as initial human capital levels, government policy, and trade policy).[2]

The Neoclassical growth theory has some key weaknesses, however. The long-run growth rate of per-capita income is explained solely by exogenous technical change--that mysterious little black box. Also, Neoclassical growth theory does not satisfactorily explain large differences in living standards, development experiences, and growth rates across countries. Comparison of the East Asian Tigers to the countries of Sub-Saharan Africa leaves the strong impression that, contrary to the dictates of Neoclassical theory, government economic policy and trade regime do matter. These weaknesses, combined with technical advances in mathematical modelling (e.g., imperfect competition), encouraged the assault on neoclassical growth theory by *endogenous growth theory*.

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[1]For full treatments of the Neoclassical theory of growth, see the relevant chapters in Barro and Sala-i-martin (1995), Blanchard and Fischer (1992), or Grossman and Helpman (1992).

[2]See Barro and Sala-i-Martin (1995, Ch 1.2)

The objective of the new growth theory is not to describe the mechanics of growth but to explain its causes. Thompson provides these criteria for endogenous growth models:

> C.1. Endogenous growth models must permit a non-zero long-run rate of per-capita welfare growth.
> C.2 The long-run rate of growth must be a function of choice variables in the model. (1994, p.1)

There are three main knowledge-based engines of the new growth theory: The human capital accumulation model (as most recently popularized by Lucas [1988]) bases growth on the individual decisions of agents investing in education. Learning-by-doing models (Romer [1986], Lucas [1988], [1993]) envision improvements in technique as a result of accumulated production experience. Finally, there are models that explain growth as an outcome of investments by firms in research and development (R&D).

It is a subclass of the latter type of endogenous growth model--Neo-Schumpeterian--which is the focus of this dissertation. Solow suggests that

> the real value of endogenous growth theory will emerge from its attempt to model the endogenous component of technological progress as an integral part of the theory of economic growth. (1994, p.51)

The Neo-Schumpeterian theory of growth aspires to exactly this. Its name arises because it formalizes Schumpeter's (1942) view of creative destruction as the engine of growth. Creative destruction is the process by which new goods are brought to the market, eroding the profits of producers of older goods.

Schumpeter's ideas have been studied at the microeconomic level for some time. The most useful models for adaption to general equilibrium models of growth are the

stochastic R&D race models of Loury (1979), Dasgupta and Stiglitz (1980a,b), Lee and Wilde (1980), and Reinganum (1985). These models capture the formal investment activities in research and development by firms attempting to maximize profits, the uncertain nature of such investments, and the prospect of winners and losers in contestable markets. General equilibrium models of monopolistic competition, such as that of Dixit and Stiglitz (1977), provide a vehicle for integrating these models into growth theory. An early endogenous growth model along this line is that of Grossman and Helpman (1989): successful innovators discover new varieties of goods, increasing consumer utility over time. Since goods are imperfectly substitutable, however, no good is ever replaced.

The first dynamic general equilibrium models to capture the process of creative destruction are those of Segerstrom, Anant, and Dinopoulos (1990) and Aghion and Howitt (1992). Elements of these two models are incorporated into a quality ladders model by Grossman and Helpman (1991b). Innovations are modeled as Poisson processes. There is free entry into stochastic R&D races in each industry. One winner discovers how to produce a product of superior quality. Concurrent races across a continuum of industries result in a certain and continuous growth rate of aggregate consumer utility. As Thompson (1994) points out, market externalities in these models move the competitive equilibrium away from the socially optimal outcome. An appropriability effect occurs, whereby the innovator cannot capture all social benefits: an intertemporal spillover effect exists because the benefits of an innovation last forever,

but the firm doesn't. An R&D subsidy or tax can achieve the socially optimal outcome. but there is no consensus on which is needed.

A second prominent feature of technical change to consider is technological diffusion--particularly imitation. Baldwin and Scott distinguish between imitation and dissemination--voluntary technology transfer by the innovator (say through licensing):

> Unauthorized imitation is a major diffusion mechanism when patents are easily circumvented, when high litigation costs and uncertainties make patents little more than a "license to sue," and when "reverse engineering," or the analysis of how a competitor's product was made, is routinely pursued. Imitation may in some circumstances augment the net social benefits from innovation by speeding diffusion and expanding an innovation's ultimate spread toward the output level where the marginal social cost of adoption equals the marginal social benefit. But, alternatively, by reducing anticipated earnings, imitation may retard the incentive to innovate. (1987. p.120)

This concept has also been studied in depth at the microeconomic level. Some of the important theoretical works which sought to understand the relationship between market structure, innovation, and imitation were Scherer (1967), Kamien and Schwartz (1978) and Nelson and Winter (1982). These efforts have uncovered a variety of possible strategic situations: market power may encourage or inhibit imitation and imitation may foster or discourage market concentration.

Several key empirical case studies by Mansfield et al. (1981), Mansfield et al. (1982), and Mansfield (1985) conclude that imitators typically take 70 percent of the time and spend 65 percent as much on R&D as the innovator: imitation lags are between one and two years; patents raise the costs of imitation but don't reduce its occurrence; the

expectation of rapid imitation does not discourage innovative activity; and cross-country imitation lags may be declining due to improvements in communication, transportation, and the increased relative importance of more easily imitated products such as software. Imitation is an important phenomenon.

Several Neo-Schumpeterian models of growth encompass the possibility of imitation. These are, almost exclusively, two-country models that examine various issues of North-South trade. The primary model is Grossman and Helpman (1991b). In their model, only the North innovates: the South gains market share by imitating and captures the market because of lower wages. This model was generalized and used to examine such issues as property rights protection (Helpman [1993], Taylor [1993a,b], [1994]) and, partial market penetration (Glass [1992]). Far less work examines imitation and trade between advanced countries. One exception, incorporating exogenous imitation into a Heckscher-Ohlin model with endogenous innovation, is Dinopoulos et al. (1993). One of the goals of this dissertation is to endogenize imitation in a model of trade between advanced countries. I regard this as an essential step in understanding the role of technology transfer at all stages of world development.

## 1.2 A Stability Consideration

Segerstrom (1991) develops a closed economy Neo-Schumpeterian model of endogenous innovation and endogenous imitation. The difficulty in endogenizing imitation is the necessity of positive expected economic profits in final goods production

to provide motivation for the potential imitator to enter into costly and risky imitative activity. In the North-South model, this is simply a matter of postulating differences in production capabilities across countries. It is a little more difficult in a closed-economy model. Segerstrom proves the existence of a steady-state Nash equilibrium in which imitators can expect to collude with the market leader and earn positive profits. I extend this model to a two-country version in which technology transfer occurs through endogenous imitation. First, however, a stability analysis proves necessary.

In Segerstrom's model, innovation and imitation are modelled as Poisson processes: there is free entry into both innovative and imitative R&D races, there is one factor of production, and unit labor requirements in each activity are constant. This model, however, has unusual comparative static results: a subsidy to innovation lowers the per industry level of innovative activity. Concurrently, a subsidy to imitation lowers imitative activity. In Chapter 2, I show that this arises from the assumption of constant unit labor requirements. By introducing specific factors to each activity, I allow for instantaneous diminishing returns to R&D and show that, when there are sufficient diminishing returns, the comparative static results are reversed: a subsidy to innovation increases the level of industry innovative activity. Similarly, a subsidy to imitation increases the level of imitative activity.

In the spirit of Samuelson's Correspondence Principle, I relate the above result to a stability analysis. I introduce ad-hoc adjustment mechanisms. These require entry into or exit from R&D races when expected discounted profits are not equal to expected discounted costs, as required for equilibrium. I find that, when instantaneous diminishing

returns to R&D are not sufficient, the model's only interior solution is locally unstable. This necessity of diminishing returns accords with several empirical studies. See Thompson (1995b) for an empirical study of, among other things, instantaneous returns to R&D in a Neo-Schumpeterian model. He finds strong evidence for diminishing returns. As it turns out, introducing diminishing returns to R&D imposes no great limitation on the usefulness of the models involved. I incorporate instantaneous diminishing returns into the two-country model of Chapter 3 of this dissertation, and study the implications of endogenous imitation for trade patterns.

## 1.3 Imitation and Trade Among Advanced Countries

Trade economists have long preached the virtue of free trade, but empirical studies have usually reported only minor static welfare losses resulting from trade restrictions.[3] The new growth theory may validate the trade theorists' policy recommendations, however, with the possibility of large dynamic effects of trade policy. Romer (1993b) shows that, in a country where lifting trade restrictions can introduce new goods into the economy, the potential welfare benefits are an order of magnitude larger than traditional welfare loss measurements. Trade restrictions can also reduce the size of potential profits to innovation, lowering the rate of innovation and growth.

[3] See Feenstra (1992) for a discussion of the empirical measurement of welfare losses.

Another benefit of the new growth models is the ability to explain changing trade patterns over time. The North-South trade models formalize Vernon's (1966) description of the product cycle. Production of new goods, introduced in the North, is eventually transferred to the South to take advantage of lower production costs. Dinopoulos et al. (1993) develop a dynamic version of the two-country Heckscher-Ohlin model. Growth is driven by endogenous innovation, and trade patterns are influenced by innovation and exogenous imitation. Interindustry and intraindustry trade, product cycles and multinationals are possible, but technology transfer is exogenous, costless, and can only occur in one direction, contrary to the evidence.[4]

Chapter 3 extends the model of Chapter 2 to a two-country integrated equilibrium world economy in which factor price equalization occurs. The model is simplified by assuming that there is now only one factor of production. Each R&D activity has a specific functional form exhibiting instantaneous diminishing returns to R&D. There is also an exogenous diffusion effect, introducing the possibility that imitative R&D activity has a positive welfare effect aside from any competitive or variety effects in the final goods market. Technology transfer can only occur through costly imitation. Two-way technology transfer and trade patterns depend on relative national labor endowments.

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[4]See the various studies by Mansfield cited above and the survey of Nadiri (1993), which enumerate the expenses incurred in efforts to transfer technology from one country to another, both cooperative and noncooperative.

## 1.4 Imitation and International R&D Knowledge Spillovers

With the advent of endogenous growth literature, R&D knowledge spillovers have come to play an important role in growth theory. Long-run growth in utility, productivity or per-capita income is still driven by technological change, but technological change is endogenized in the Neo-Schumpeterian literature. It arises from investment in R&D. But, are there long-run diminishing returns to R&D, as there are to additions to the capital stock?[5] Formal Neo-Schumpeterian modelling generally side-steps this question by assuming that, in the steady-state, the expected costs of discovering each new higher quality product are no larger than the expected costs of discovering the last. Each new increment in knowledge is achieved at constant cost. This assumption of constant returns to scale (CRS) in R&D is justified by the notion that there are spillovers of knowledge from current innovations that aid in subsequent innovations and exactly offset any long-run diminishing returns. There is no attempt to identify the mechanisms by which these spillovers are accomplished.

In addition to the importance of spillovers in long-run growth, Neo-Schumpeterian literature also assigns importance to them in interactions among countries. Generally, anything which increases the profitability of national R&D increases growth. Thus, the

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[5]These long-run diminishing returns to R&D should be distinguished from the instantaneous diminishing returns to R&D discussed above. The former occurs, for example, if a given stock of basic knowledge offers a fixed amount of exploitable ideas. Although basic research is often considered to have nondecreasing long-run returns ( See Romer [1993b]), it may or may not accumulate fast enough to counteract diminishing returns to the current stock. Instantaneous diminishing returns can occur at the industry level if there are fixed factors, such as skilled labor, in R&D activity.

importance of free trade comes to the forefront of policy discussions because of the large potential growth effects of increases in market size. It is also true that policies which increase the effectiveness of accessing foreign knowledge, thus increasing the productivity of home R&D efforts, will accelerate growth.[6] These may or may not be free trade policies. Whatever the case, it seems advisable to delve deeper into the nature of international R&D knowledge spillovers.

Recent empirical literature tries to quantify the magnitude and extent of international R&D spillovers. Two key related questions are at the center of attention: Is there a significant geographic dimension which may imply advantage to the country of origin for any given innovation? What is the relative contribution to, say, productivity growth of domestic and foreign R&D efforts? Griliches (1992) surveys the literature and concludes that R&D spillovers are both prevalent and important. Nadiri (1993), in an extensive survey, concurs, citing evidence that firms must incur R&D expenses to realize the benefits of knowledge spillovers, and presenting findings that spillovers may be stronger within than among countries. Irwin and Klenow (1994), however, present evidence that spillovers flow freely across borders.[7] Coe and Helpman (1993) conclude that spillovers to trading partners amount to 25 percent of the world return to R&D conducted by the seven largest OECD economies. A ubiquitous finding of this type of

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[6]See Dinopoulos and Kreinin (1994), Ruffin (1994) and Brecher, Choudri and Schembri (1994) for examples of models that exhibit this effect.

[7]Irwin and Klenow's study looks at the semiconductor industry because it is considered a strategic industry. The study uses data on average industry selling price and firm shipments. The findings on spillovers lead the authors to conclude that there is no justification for a national R&D subsidy to that industry.

study is that foreign R&D has a stronger total effect on factory productivity than domestic R&D.

The theoretical implications of the model developed in Chapter 3 suggest a more complex relationship between trade and international R&D knowledge spillovers than implied by most existing studies. In particular, the model implies that some R&D expenditures are innovative and some imitative. I argue in Chapter 4 that ignoring this difference introduces bias into estimates of the magnitude of spillovers, and leads to misinterpretation of the relative contributions of foreign and domestic R&D. I first discuss the concept of spillovers in depth, stressing the need for engaging in R&D activity in order to capture true spillovers of knowledge from the R&D activities of others. I next develop an equation of knowledge accumulation and technology transfer consistent with the model of Chapter 3 and compare it to some existing literature. The chapter concludes with some thoughts on the measurement of spillovers.

# CHAPTER 2
# STABILITY IN NEO-SCHUMPETERIAN MODELS OF GROWTH

## 2.1 Introduction

The new growth literature is experiencing a few growing pains. Economists' use of new mathematical tools opens up new modeling possibilities unparalleled in traditional Solovian growth models, yet the simplifying assumptions which make these models workable sometimes lead to trouble. Devereux and Lapham (1994), for example, discuss a stability problem in the knowledge-driven model of new product innovation of Rivera-Batiz and Romer (1991). A branch of Neo-Schumpeterian growth theory, beginning with the work of Grossman and Helpman (1991b), has a similar stability problem. This chapter shows that introducing instantaneous diminishing returns to R&D activity resolves the stability problem.

Recall from Chapter 1 that Segerstrom (1991) extends Grossman and Helpman's (1991b) model of quality growth. He incorporates endogenous innovative and imitative R&D activities into a closed-economy one-factor model of growth. It is one of two Neo-Schumpeterian models of growth incorporating endogenous imitation.[1] The model generates counter-intuitive comparative static results: when a subsidy to innovative R&D

[1] The alternative is the product cycle model of Grossman and Helpman (1991a).

is introduced, the intensity of innovative activity falls. The same is true of a subsidy to imitation.

This chapter shows that these perverse comparative-static results arise because the model is unstable. The problem is the use of linear R&D unit costs. By introducing a more general cost function, I show that the instability can be eliminated and the unusual comparative static results reversed. This occurs when there are sufficient instantaneous diminishing returns to R&D. Segerstrom (1994) and Cheng and Tao (1993) address similar issues. Segerstrom shows that the quality ladders model of Grossman and Helpman (1991b) is not stable when all industries are not subsidized and uncertainty about which industries will be subsidized exists. Cheng and Tao replace the linear costs of Segerstrom (1991) with quadratic costs and show that this reverses the comparative static results. They do not conduct a stability analysis or derive stability conditions. This chapter looks explicitly at the relationship between the stability analysis and the comparative static results.

Section 2.2 sets out the model and establishes the existence of equilibrium (Proposition 1). Section 2.3 examines the stability of the model and develops the connection with the comparative static results of subsidies to innovation and imitation (Proposition 2). Section 2.4 provides a numerical example. A final section offers concluding remarks.

## 2.2 Introducing Specific Factors

### 2.2.1 The Model

This is a dynamic general equilibrium model with a final goods sector and an R&D sector. Quality-improving innovations occur stochastically over time in a continuum of industries producing final goods. These, in turn, augment utility because firms cannot appropriate all of the returns to innovation. A representative agent has a Cobb-Douglas instantaneous utility function with perfect substitutes (CDP). The agent maximizes utility over time and over the continuum of final goods. Profit-maximizing firms use consumer savings to hire labor and undertake R&D.

There are two types of R&D, both of which are modeled as Poisson processes. Costly and risky innovative R&D is undertaken in each industry, under conditions of free entry, by firms hoping to be the first to discover the next highest-quality product and enjoy temporary monopoly profits. Following this innovation, costly and risky R&D is undertaken in each industry to copy the latest state-of-the-art product. The firm learning how to duplicate the product first is able to share collusive profits with the leader in the industry. Growth in consumer utility is endogenously generated by firms choosing R&D expenditures optimally.

There are three factors of production. Production of final goods exhibits CRS in labor. Entry into final goods production, however, requires the successful acquisition of knowledge (innovation or imitation). In addition to labor, the production of innovative activity requires a fixed specific factor, capital, as does the production of imitative

activity.[2] Both factor markets are competitive, and CRS prevails in both R&D activities. In the presence of fixed factors, however, both innovation and imitation will exhibit aggregate industry instantaneous diminishing returns to R&D.

In the steady state, consumer expenditures, the interest rate, and the percentage of industries with one quality leader are constant. The intensities of innovative and imitative activity are also constant. Innovation and imitation are exponentially distributed events. The pace of these events is governed by the constant intensity of R&D efforts. In the steady-state equilibrium, the market structure of each industry alternates between a monopoly targeted for an imitation race and a duopoly threatened by an innovation race. Although the current quality leader(s) capture the entire market in each industry, producers of previous state-of-the-art goods force limit pricing on the monopolist and/or collusive duopoly.

There are R&D knowledge spillovers from innovation to imitation because the unit costs of imitation are always lower in the steady state than the unit costs of innovation. There are also exogenous R&D spillovers from one product cycle to the next because the expected costs of successively larger innovations stay constant. These spillovers will be discussed, in depth, in Chapter 4. In the next several pages, the model is briefly developed.

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[2]That innovation and imitation activity may have specific capital in the short run has support in the literature. It is often different types of firms that innovate and imitate. See Baldwin and Scott (1987). See also Jovanovic and MacDonald (1994) who argue that innovation and imitation are substitutes in that firms may compete for market share by either method.

2.2.1.1 Consumer behavior

A continuum of final goods industries is indexed by $\omega \in [0,1]$. Each industry has an countably infinite number of potential qualities, $j=0,1,\ldots$, increasing in j. Only a subset of these qualities has been, as yet, discovered at time t. A representative infinite-lived consumer maximizes lifetime utility, given by

$$U = \int_0^\infty e^{-\rho t} z(t)\, dt \quad . \tag{2.1}$$

with subjective discount rate $\rho$ and instantaneous utility

$$z(t) = \int_0^1 \ln\left[\sum_{j=0}^{\infty} \lambda^j d_{jt}(\omega)\right] d\omega \quad , \tag{2.2}$$

in which $d_{jt}(\omega)$ is the quantity consumed at time t, in industry $\omega$, of quality j. The measure of quality improvement of the $j^{th}$ quality over the $j-1^{th}$ quality is $\lambda$, which is greater than one by assumption. Let $h_t(\omega)$ represent the state-of-the-art quality at time t in industry $\omega$. Then, it increases utility relative to the lowest quality available by $\lambda^{h_t(\omega)}$. Because of the stochastic nature of innovation, $h_t(\omega)$ will vary across industries.

As indicated in the next subsection, the current quality leader(s) can always capture the market by charging a limit price determined by its degree of quality advantage because, given equal quality-adjusted prices, the consumer is assumed to choose the highest quality available. The instantaneous demand function maximizes instantaneous utility for given instantaneous expenditures, E(t):

$$d_{jt}(\omega) = \begin{cases} \dfrac{E(t)}{p_{jt}(\omega)} & \text{if } j = h_t(\omega) \\ 0 & \text{else} \end{cases} \quad . \tag{2.3}$$

The price, at time t, of the $j^{th}$ quality in industry $\omega$, $p_{jt}(\omega)$, is taken as given by the consumer. The time path of expenditure that maximizes lifetime utility is

$$\frac{\dot{E}(t)}{E(t)} = r(t) - \rho \quad . \tag{2.4}$$

Aggregate expenditure is determined in the steady state by the value of assets, and r(t) is the instantaneous interest rate. Equations 2.3 and 2.4 are derived in Appendix A.

2.2.1.2 Asset market

In the asset market, savings are supplied to firms to finance R&D expenditures. In a typical R&D race, each firm issues a stream of Arrow-Debreu securities for the duration of the race. The proceeds are just enough to cover the firm's R&D expenditures. Each security pays out the expected discounted profits of the successful firm, contingent on the firm winning the R&D race at the instant the security is issued, and zero otherwise. Since there is a continuum of industries, the industry-specific uncertainty involved with R&D can be eliminated by the consumer who invests in diversified mutual fund portfolios. In the steady-state equilibrium, the instantaneous interest rate equals the riskless rate.[3]

2.2.1.3 Production and entry

As the name implies, a property of the CDP utility is that, at equal quality-adjusted prices ( $p_{jt}(\omega)/\lambda^j = p_{it}(\omega)/\lambda^i$ ), consumers are indifferent to the various available qualities within an industry. Assume that indifferent consumers will always choose the higher quality. Take labor as the numéraire so that w = wage = 1. Since

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[3]See Dinopoulos (1994) for a detailed explanation of the asset market in these types of models.

previous quality producers are willing to supply at marginal cost ($p=1$), current leaders can only markup the price by as much as the consumer values the current quality over the previous quality. A price higher than $\lambda$ is never optimal since the within-industry price elasticity of demand is infinite, meaning the consumer would switch entirely to the lower quality. So, $p = \lambda$ in each industry at all times in the steady state. Appendix C shows that, in this model, an industry leader never leads by more than one step up the quality ladder because leaders never innovate. This is not as unreasonable a characteristic, empirically, as it sounds because, as discussed below, this is a model of major innovations.

Final goods production is such that one unit of output is produced by one unit of labor for all products and qualities. To produce the final good, however, firms must learn how to do so by investing in R&D and winning innovative R&D races. The first firm to innovate in industry $\omega$ becomes the sole producer in that industry. This industry is then targeted for an imitative R&D race. The winner will learn how to copy the production method of the latest quality product and collude with the current leader.[4] The next round of innovative R&D races will result in discovery of the next quality level, a new industry leader and so on.

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[4]Segerstrom(1991) proves that a Nash equilibrium steady state exists in which imitators collude with quality leaders in the production of final goods and so can expect to make positive profits. The latter is required for costly imitative R&D activity to exist. This specification of imitation is made for simplicity. An alternative specification in which imitation is in the form of horizontal differentiation is taken up in Dinopoulos (1992).

2.2.1.4 Research and development

By engaging in i (or c) units of innovative (or imitative) activity each moment, a firm 'buys' the probability idt (or cdt) of successfully carrying out the next innovation (or imitation) in the industry in the interval dt. I (or C) is the total level of innovative (or imitative) activity in each industry targeted for innovation (or imitation) at each moment.[5] Idt is the constant probability that, if the innovation does not occur by time t, it will by time t + dt. The time duration of each R&D race is exponentially distributed in the steady state; the hazard rate is the intensity of R&D activity (I or C). Innovation and imitation races in each industry are subject to free entry, which will occur until expected discounted profits are driven to zero.

The specific factors in R&D are not specific to an industry but to a particular activity--innovation or imitation. This implies aggregate diminishing returns to each activity. Since there is a continuum of industries, no one industry (or firm) is large enough to affect the returns to the specific factors. All industries are identical, however, so a representative industry can be thought of for which the specific factor is fixed in the steady state. This is because the fixed endowment of each specific factor is employed equally among the fraction of industries targeted for innovation or imitation. In the steady state this fraction is constant. Firms are atomistic in each industry at this stage and can hire labor and capital freely. The number of firms engaged in R&D is indeterminant, but not the number of producers.

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[5]To avoid cumbersome notation, and because I and C are constant in the steady state, I and C are not explicitly shown to be functions of time.

2.2.1.5 Innovation

Labor employed in innovative activity in each industry is $L_I$ , $K_I$ is capital employed, and I is the intensity of innovative activity for the representative industry targeted for innovation. Production can be described by the unit cost function. Let $w_I$ be the return to capital, $a_{LI}$ , the unit labor requirement, and $a_{KI}$ , the unit capital requirement ($w_I$, $a_{LI}$ and $a_{KI}$ are shown, in Appendix B, to be functions of I). Firms are assumed to be atomistic, capital is fixed, and a Cobb-Douglas production function is adopted for convenience. Appendix B derives the following expression for unit costs:

$$u_I = a_{LI} + w_I a_{KI} = a_I I^{\theta} \quad . \tag{2.5}$$

In equation 2.5, $\theta = \frac{1-\epsilon}{\epsilon}$ , $\epsilon$ is labor's share in innovative costs, and $a_I$, defined in Appendix B, is a function of parameters and $K_I$. Intuitively, aggregate per-industry capital is fixed. As I rises, the return to $K_I$ rises relative to that of the mobile factor, $L_I$. Thus, $\partial u_I / \partial I = (du_I / dw_I)(\partial w_I / \partial I) > 0$. The advantage of introducing specific factors is that, even though production at the firm level exhibits CRS, the representative industry (or economy-wide aggregate innovative activity) is subject to diminishing returns.

2.2.1.6 Imitation

The amount of labor employed in imitation is $L_C$, $K_C$ is the level of capital, and C is the aggregate level of imitative activity for the representative industry subject to imitation. Let $w_C$ be the return to capital in imitation, $a_{LC}$ be the unit labor requirement,

and $a_{KC}$ be the unit capital requirement ($w_C$, $a_{LC}$ and $a_{KC}$ are functions of C). With firms small, with capital fixed, and with a Cobb-Douglas production function, unit costs are

$$u_C = a_{LC} + w_C a_{KC} = a_C C^{\phi} \quad . \tag{2.6}$$

In (2.6), $\phi = \dfrac{1-\gamma}{\gamma}$, $\gamma$ is labor's share in imitation costs, and $a_C$, defined in Appendix B, is a function of production function parameters and $K_C$. Hence, $\partial u_C / \partial C = (du_C / dw_C)(\partial w_C / \partial C) > 0$.

2.2.2 Market Equilibrium

2.2.2.1 Product market

Because the total number of industries is of measure one, consumer demand in each industry is given by (2.3). As noted, quality leaders can capture the market by charging $p = \lambda$. A quality leader has a constrained monopoly in equilibrium, and the monopoly profits are given by

$$\pi_L = (\lambda - 1)\left(\frac{E(t)}{\lambda}\right) = \left(1 - \frac{1}{\lambda}\right)E(t) \quad . \tag{2.7}$$

in which $(\lambda-1)$ is the markup and $E(t)/\lambda$ is quantity demanded in each market. After imitation occurs, there are two quality leaders who collude, continue to charge price $p = \lambda$ and divide the market equally. Profits to each are

$$\pi_C = \left(1 - \frac{1}{\lambda}\right)\frac{E(t)}{2} \quad . \tag{2.8}$$

An important implication of the foregoing discussion is that price is constant over time and across industries. Collusion turns out to be a fairly convenient method of allowing for positive expected profits to imitation.

2.2.2.2 Labor market

Labor is homogeneous, the economy has an endowment of $\bar{L}$, and the labor market clears at each moment in time. Labor demand comes from three sources--production, imitative R&D, and innovative R&D. Since one unit of labor produces one unit of final product, the demand for labor, at time t, in final goods production equals $\frac{E(t)}{\lambda}$. The unit labor requirement for innovation is $a_{LI}$, so $a_{LI}I$ is the labor demand for innovative R&D, at each time t, in each industry targeted for innovation. Similarly, $a_{LC}C$ is the labor demand for imitative R&D, at each time t, in each industry targeted for imitation. Let $\beta(t)$ be the fraction of industries (duopolies) targeted for innovation, and $\alpha(t)$ be the fraction of industries (monopolies) targeted for imitation. Total R&D labor demand is $\beta(t)a_{LI}I+\alpha(t)a_{LC}C$. The full employment condition, at time t, is (using (2.5), (2.6), and the definitions of $a_{LC}$ and $a_{LI}$ in Appendix B)

$$\bar{L} = \frac{E(t)}{\lambda}+\beta(t)a_{LI}I+\alpha(t)a_{LC}C = \frac{E(t)}{\lambda}+\epsilon a_I\beta(t)I^{\theta-1}+\gamma a_C\alpha(t)C^{\phi-1}. \tag{2.9}$$

2.2.2.3 Specific factors

The returns to capital, $w_I$ and $w_C$, adjust to ensure that the aggregate amount of each specific factor $(\bar{K}_I, \bar{K}_C)$ is always fully employed. The full-employment conditions are

$$\bar{K}_I = a_{KI}I\beta(t) \Rightarrow K_I = \bar{K}_I/\beta(t) \tag{2.10}$$

and

$$\bar{K}_C = a_{KC}C\alpha(t) \Rightarrow K_C = \bar{K}_C/\alpha(t) \quad . \tag{2.11}$$

### 2.2.3 Steady State

#### 2.2.3.1 Characteristics

This paper considers a symmetric Nash equilibrium steady state in which consumer expenditures and the proportion of industries with one quality leader are assumed to be constant over time. However, since the focus is on the equilibrium levels of I and C, an equivalent representation of the steady state is developed. The model is reduced to two equations in I and C. Segerstrom (1991) and Segerstrom and Davidson (1991) show that innovators will collude with one and only one imitator and that quality leaders will not collude with previous state-of-the-art producers. This is true if

$$\ln 2 > (\rho + I^*) \ , \qquad \textbf{Assumption A1}^{6}$$

$$\ln\left(\frac{3}{2}\right) < \rho\Delta \ , \qquad \textbf{Assumption A2}$$

and

$$\lambda > \max\left\{\frac{1}{(1 - e^{-\rho\Delta})} \ , \ 3\right\} \ . \qquad \textbf{Assumption A3}$$

In Assumptions A2 and A3, $\Delta$ is the lag before a cheater can be detected violating the collusive agreement and punished.[7]

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[6]The * denotes a steady-state value.

[7]In Chapter 2, Assumption A1 can be satisfied by choosing the labor endowment sufficiently small such that $I^*$ is small enough to satisfy the inequality. In Chapter 3, with $I^*$ always less than one, Assumption A1 will be satisfied if $\ln 2 > 2\rho\Delta$. This inequality and Assumption 2 allow a range of $\Delta$ which satisfy the model. Assumption A3 can be satisfied, for given $\Delta$ and $\rho$, by a sufficiently large quality increment, $\lambda$. This is a model that considers large innovations.

The steady state has the same characteristics as Segerstrom (1991): [1]. E and $\alpha$ are constant over time, by assumption; [2]. $r(t) = \rho$ , which follows from characteristic [1]. and equation 2.4: [3]. I (or C) is constant across time and industries targeted for innovation (or imitation), by the assumption of symmetry, the fact that price is constant across time and from characteristic [1], above: [4]. One quality leader earns $\pi_L$, as shown in equation 2.7, and two quality leaders earn $\pi_C$, as shown in equation 2.8: [5]. There are only two types of industries--those with one leader and those with two leaders; [6]. In industries with one leader, there is no innovative R&D and previous quality leaders don't imitate; [7]. In industries with two quality leaders, there is no imitative R&D and, neither current nor previous leaders innovate. Characteristics [5] - [7], listed above, are proven in Appendix C.

2.2.3.2 Industrial targeting

Since innovation (or imitation) is governed by a Poisson process, in an interval of time, dt, an industry becomes an $\alpha$ ($\beta$) industry with probability Idt (Cdt). The proportion of industries becoming $\alpha$ industries in dt is $\beta I dt$. The proportion of industries becoming $\beta$ industries in dt is $\alpha C dt$. So, $\beta = 1 - \alpha$ and $\dot{\alpha}(t)$ obeys

$$\dot{\alpha}(t) = (1 - \alpha(t))I(t) - \alpha(t)C(t) \quad . \tag{2.12}$$

In the steady state, $\dot{\alpha}(t) = 0$, so $\alpha Cdt = \beta Idt$ and

$$\alpha C \quad (1 \quad \alpha)I \quad \Rightarrow \alpha \quad \frac{I}{I+C} , \quad \beta \quad \frac{C}{I+C} \quad . \tag{2.13}$$

The number of industries changing from one to two quality leader(s) equals the number of industries changing from two to one leader(s).

2.2.3.3 Zero-profit conditions

Expected discounted collusive profits in the steady state are

$$v_C = \int_0^\infty \left( \int_0^\tau \pi_C e^{-\rho t} dt \right) I e^{-I\tau} d\tau = \frac{\pi_C}{\rho + I} \ .$$

in which $\rho = r(t)$ is used. The random time until the next innovation, $\tau$, is exponentially distributed. Let s be the random time until imitation. The expected discounted benefits to engaging in imitative activity are

$$b_C = \int_0^\infty (Ce^{-Cs}) v_C e^{-\rho s} ds = \frac{Cv_C}{(\rho + C)} \ .$$

Total costs at t are unit cost times C, so the expected discounted costs from engaging in imitative activity are

$$\int_0^\infty \left\{ \int_0^t u_C C e^{-\rho s} ds \right\} Ce^{-Ct} dt = \frac{Cu_C}{\rho + C} \ .$$

recalling that $u_C$ is as given in equation 2.6. Combining these two gives expected profits from engaging in imitative activity and the zero-profit-in-imitation-condition is

$$v_C = \frac{\pi_C}{\rho + I} = u_C \ . \tag{2.14}$$

The ZPC (zero-profit condition) in innovation is developed in a similar manner. Innovators, however, have two components to profits. From the point of innovation until the point of imitation, the innovator earns profits $\pi_L$, given in equation 2.7. After imitation, the innovator shares the market with the successful imitator. Because $\tau$, the time duration of the imitation race, is exponentially distributed, $v_I$, the expected discounted reward from innovating is

$$v_I = \int_0^\infty \left\{ \left( \int_0^\tau \pi_L e^{-\rho t} dt \right) + e^{-\rho\tau} v_C \right\} Ce^{-C\tau} d\tau = \frac{(\pi_L + Cv_C)}{(\rho + C)} \ .$$

Analogous to imitation, the ZPC for innovation is

$$v_I = \frac{\pi_L + Cv_C}{\rho + C} - u_I \ . \tag{2.15}$$

### 2.2.3.4 Steady-state equilibrium

The next step is to reduce the model to two equations in C and I and examine the steady-state equilibrium of the model. To obtain a steady-state labor market condition, use (2.13) in (2.9):

$$\bar{L} = \left(\frac{C}{I+C}\right) a_{LI} I + \left(\frac{I}{I+C}\right) a_{LC} C + \frac{E}{\lambda} = \left(\frac{IC}{I+C}\right)(a_{LI} + a_{LC}) + \frac{E}{\lambda} \ . \tag{2.16}$$

By substituting for E from (2.8) and for $\pi_C$ from (2.12), the equilibrium labor constraint becomes

$$\frac{(\lambda - 1)}{2}\left(\bar{L} - (a_{LI} + a_{LC})\frac{IC}{I+C}\right) = (\rho + I)u_C \ . \tag{2.17}$$

This equation implicitly defines C as a function of I, denoted $C_L(I)$. The properties of $C_L(I)$ are derived in appendix D. $C_L(I)$ is negatively sloped with a positive intercept. This equation is graphed in Figure 2.1 (for $\phi > 0$).

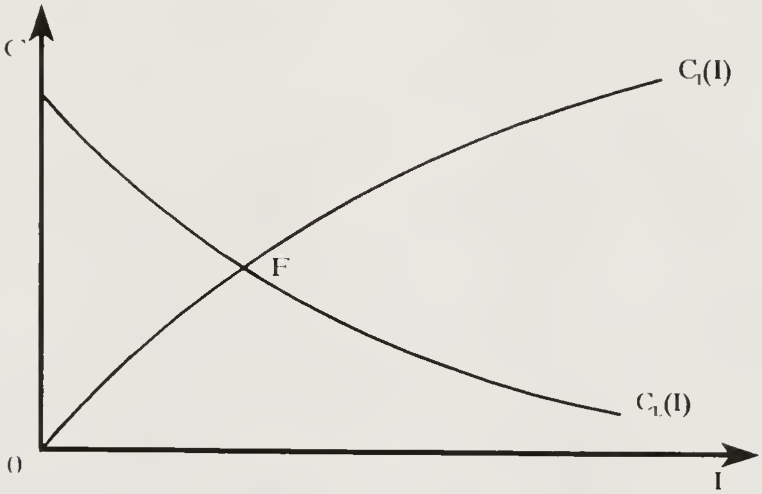


Figure 2.1
The Unique Steady-State Equilibrium

To obtain a steady-state ZPC in R&D, combine (2.7), (2.8), (2.14) and (2.15):

$$u_I = \frac{(2(\rho+I)+C)u_C}{\rho+C} \quad . \tag{2.18}$$

Equation 2.18 defines $C_I(I)$, the equilibrium ZPC in R&D. If three conditions--R1, R2, and R3, derived in Appendix D--hold, $C_I(I)$ will be positive and positively sloped. Restriction R1 is discussed in section 2.4. Restrictions R2 and R3 are equivalent to the stability conditions derived in the next section. $C_I(I)$ is also graphed in Figure 2.1, and it's properties are derived in Appendix D. The following proposition summarizes this section:

***Proposition 1***

*The Nash Equilibrium steady state represented by F in Figure 2.1 exists and is unique.*

## 2.3 Stability and Comparative Statics

Samuelson (1983) explains the duality between stability analysis and meaningful comparative static results, which he calls the Correspondence Principle. To apply this principle, one postulates an adjustment process, presumably based on rational economic behavior, whereby the equilibrium condition is achieved. Then, one ascertains under what conditions, after a small disturbance, this process returns the economy to equilibrium. This is Samuelson's "stability analysis of the first kind in the small." (1983, 258) Samuelson shows, as I do below in this case, that these stability conditions rule out perverse comparative statics.

2.3.1 Stability

I will consider only local stability. Recall that unit costs for innovation and imitation are $u_I \quad a_I I^\theta$ and $u_C \quad a_C C^\phi$, respectively. At $\theta = \phi = 0$ ($\epsilon = \gamma = 1$), the model reduces to Segerstrom's (1991) model. At $\theta = \phi = 1$ ($\epsilon = \gamma = .5$), the model corresponds in reduced form behavior to Cheng and Tao (1993). First, I demonstrate that, at $\theta = \phi = 0$, the model has no stable interior equilibrium. Then, I derive stability conditions for the general model.

The transitional behavior of the state variable, $\alpha(t)$, will depend on the adjustment of industry innovative and imitative activity (see equation 2.14) in response to nonzero profits. To analyze the behavior of this model in the neighborhood of the steady state, assume that the intensities of industry innovation and imitation obey the following adjustment rules:

$$\dot{I}(t) \quad \Psi(v_I \quad u_I) \tag{2.19}$$[8]

and

$$\dot{C}(t) \quad \Gamma(v_C \quad u_C). \tag{2.20}$$

in which $\Psi(0) = \Gamma(0) = 0$ and $\Psi'(\cdot), \Gamma'(\cdot) > 0$. The functions $\Psi$ and $\Gamma$ convey continual entry into (or exit from) R&D races whenever expected profits are $>$ ($<$) 0. For stability, this behavior must return the model to the steady state, in which $\dot{C} = 0$ and $\dot{I} = 0$, after a disturbance. Because this model has specific capital, the adjustment rules can be thought of as being based on capital movements with adjustment costs in response to rental differentials, as in Neary (1982). This paper examines local stability, so it is

[8]The $\cdot$ denotes a time derivative.

enough to see that a rental differential would occur ($w_I \neq w_C$). By the 'magnification effect' of Jones (1971), in a three factor model, the change in relative expected benefits is always trapped between the returns to specific factors. So, for example, a small increase in $v_I$ from F will cause a rental differential in favor of innovative capital.

Substituting into (2.19) from (2.5), (2.7), (2.8), (2.14), (2.15), and (2.16) gives $\dot{I}(t) = 0$ in terms of I and C:

$$\frac{(\lambda - 1)}{2}\left(\bar{L} - \frac{IC}{I+C}\left(\epsilon a_I I^{\theta} + \gamma a_C C^{\phi}\right)\right) = \frac{a_I I^{\theta}(\rho+I)(\rho+C)}{2(\rho+I)+C}. \tag{2.21}$$

Substituting into (2.20) from (2.6), (2.8), (2.14), and (2.16) gives $\dot{C}(t) = 0$, which is the same as (2.17) in the specific Cobb-Douglas form:

$$\frac{(\lambda - 1)}{2}\left(\bar{L} - \frac{IC}{I+C}\left(\epsilon a_I I^{\theta} + \gamma a_C C^{\phi}\right)\right) = a_C C^{\phi}(\rho+I) . \tag{2.22}$$

The slopes of these two functions are derived below and shown to be less than zero for all nonnegative $\theta$, $\phi$.

When $\theta = \phi = 0$, $\dot{C} = 0$ and $\dot{I} = 0$ can be graphed as in Figure 2.2. The values of the various intercepts are given in Appendix D. But when $\theta$, $\phi$ are large enough, as I show below, $\left.\frac{dC}{dI}\right|_{\dot{I}=0} > \left.\frac{dC}{dI}\right|_{\dot{C}=0}$ and $\dot{I} = 0$ and $\dot{C} = 0$ can be graphed as in Figure 2.3. The values of $C_0$ and $I_0$ are given in Appendix D. Comparison of Figures 2.2 and 2.3 shows that $\dot{I} = 0$ cuts $\dot{C} = 0$ from below in Figure 2.2 and from above in Figure 2.3. Using (2.21) and (2.22), it is straightforward to show that, in either case, for given C, I above $\dot{I} = 0$ implies $\dot{I} < 0$ and vice versa. Similarly, for given I, C to the right of $\dot{C} = 0$ implies $\dot{C} < 0$ and vice versa. These arguments are derived in Appendix E and are indicated by the arrows in each phase diagram.

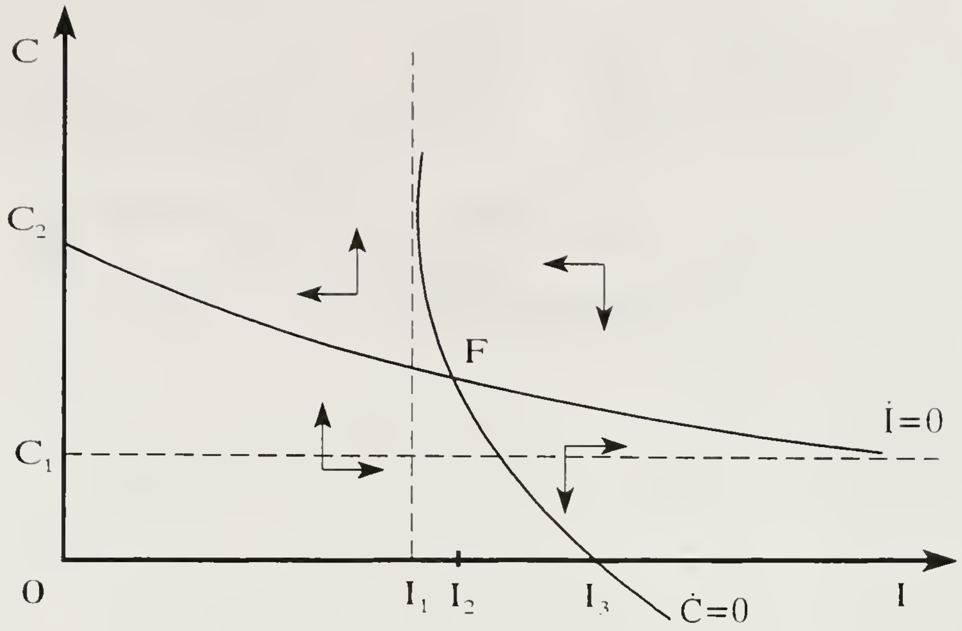


Figure 2.2
The Unstable Case

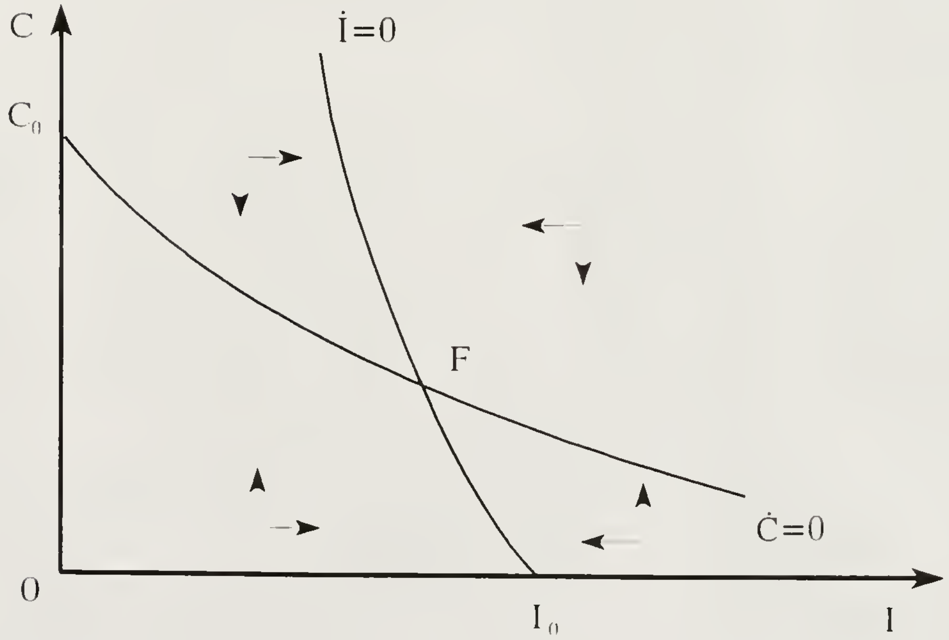


Figure 2.3
The Stable Case

It is apparent that F in Figure 2.2 is not locally stable. To find the stable equilibria in the case of $\epsilon = \gamma = 1$, the extremes of the model are examined. A disturbance away from F to the northwest will imply $C \to \infty$, $I \to 0$ and then, since all $\alpha$ industries will be eventually imitated, $C \to 0$.[9] This means that $I = C = 0$, the no-growth trap of Aghion and Howitt (1990), is one stable equilibrium. It is stable because a disturbance away from (0,0) would require $I > 0$ first. Since only a countable number of industries would experience innovation at any given point in time, $C \to \infty$ in those industries and innovative activity would cease. As $C \to 0$ to the southeast of F, $I \to \infty$ and $\beta \to 0$. When $C = 0$, innovators are no longer in danger of imitation, but are threatened by further innovation. Then $v_I = \pi_L/(\rho+I)$, $C = 0$, and $I = (\pi_L/a_I) - \rho$ (which equals $I_2$ in Figure 2.2) is the second stable equilibrium when $\theta = \phi = 0$.

In contrast, F in Figure 2.3 is a unique, interior, locally stable equilibrium. So, for the model to be locally stable, it must be that $\left.\frac{dC}{dI}\right|_{\dot{I}=0} > \left.\frac{dC}{dI}\right|_{\dot{C}=0}$ in absolute value in the neighborhood of F. By differentiating (2.21) and (2.22) and comparing these slopes at the steady-state equilibrium, it is possible to derive the restrictions on $\theta$ and $\phi$ such that local stability occurs. Differentiating (2.21) and (2.22) gives

$$\left.\frac{dC}{dI}\right|_{\dot{I}=0} = \frac{\left[X + \dfrac{\theta(\rho+I)a_I I^{\theta-1}(\rho+C) + a_C C^{\phi-1}}{(2(\rho+I)+C)}\right]}{\left[Y + \dfrac{a_I I^{\theta}(\rho+I)(\rho+2I)}{(2(\rho+I)+C)^2}\right]} \tag{2.23}$$

---

[9] As C increases and I decreases, $\alpha$ falls and ever fewer industries are subject to innovation and this process accelerates over time. As $\alpha \to 0$, $C \to \infty$. Because each industry is infinitesimal, it is possible to have $C \to \infty$ in an individual industry even if L is finite.

and

$$\left.\frac{dC}{dI}\right|_{\dot{C}=0} = -\frac{\left[X + a_C C^{\phi}\right]}{\left[Y + \phi a_C C^{\phi-1}(\rho+I)\right]} . \tag{2.24}$$

(Notice that (2.23) and (2.24) are negative.) In (2.23) and (2.24),

$$X = \frac{(\lambda-1)}{2}\left(\frac{C^2}{(I+C)^2}(\epsilon a_I I^{\theta} - \gamma a_C C^{\phi}) + \frac{IC}{(I+C)}\theta\epsilon a_I I^{\theta-1}\right)$$

and

$$Y = \frac{(\lambda-1)}{2}\left(\frac{I^2}{(I+C)^2}(\epsilon a_I I^{\theta} + \gamma a_C C^{\phi}) - \frac{IC}{I+C}\phi\gamma a_C C^{\phi-1}\right) .$$

Stability can be assured if

$$\frac{(\theta(\rho+I)a_I I^{\theta-1}(\rho+C)) + a_C C^{\phi-1}}{2(\rho+I)+C} \geq a_C C^{\phi} \tag{2.25}$$

and

$$\phi a_C C^{\phi-1} \geq \frac{a_I I^{\theta}(\rho+2I)}{(2(\rho+I)+C)^2} , \tag{2.26}$$

with one or both holding with strict inequality. By substituting from (2.18) for $(\rho+C)/(2(\rho+I)+C)$ and cancelling terms, (2.25) reduces to $\theta \geq 2I/(2(\rho+I)+C)$, which holds if

$$\theta \geq 1 \text{ or } \epsilon \leq 1/2 . \tag{SC1}$$

By rearranging (2.26),

$$\phi > \left(1 - \frac{a_C C^{\phi}}{a_I I^{\theta}}\right)\left[\frac{C}{(\rho+C)}\right] ,$$

and since the bracketed term is less than one, and the term in parentheses is at most ½ by (R1), given on page 35 below, then,

$$\phi \geq \tfrac{1}{2} \text{ or } \gamma \leq \tfrac{2}{3} . \tag{SC2}$$

(SC1) and (SC2) are sufficient conditions for stability so long as at least one holds with strict inequality. These require sufficient diminishing returns to innovation and imitation.

Why are diminishing returns so important? Examination of the ZPCs, (2.14) and (2.15), provides an answer. In a partial equilibrium sense, in any industry where profits are positive, it must be that free entry into that market drives them to zero. Otherwise, entry continues unabated, and the ZPC is never satisfied. In this model, free entry does not directly lower the expected benefits so it must raise costs. Suppose that a disturbance causes $v_I > u_I$. If $u_I$ is constant, the only way to reequate (2.14) is for C to rise since $\partial v_I/\partial C < 0$. Operating through the labor constraint, I falls. If $u_I$ increases only slowly with I then $v_I$ might rise faster than $u_I$ as I rises, widening the gap. This is because I rising makes $v_C$ fall so that $v_C < u_C$. C falling in response (by a relatively larger amount the less $u_C$ rises with C) will increase $v_I$, possibly more rapidly than $u_I$. Profits would increase and equilibrium would not be reestablished. If there are sufficient diminishing returns to scale in R&D (i.e., (SC1) and (SC2) hold), then $u_I$ rises more rapidly than $v_I$ as I rises and this reequates expected profits to zero.

### 2.3.2 Comparative Statics

It follows directly from the stability analysis that the comparative static results depend on whether (SC1) and (SC2) hold. Suppose the government gives a lump sum per unit subsidy to innovative R&D. It is not difficult to show that a small subsidy will shift $\dot{I}$ up in Figures 2.2 and 2.3 resulting in a lower I and higher C in Figure 2.2 and a higher I and lower C in Figure 2.3. A subsidy to C will also shift $\dot{C}$ out, increasing

C and decreasing I if the model is locally stable. Intuitively, perverse comparative static results in the neighborhood of F are eliminated when the model becomes locally stable. This is the Correspondence Principle. Comparative static results are derived in Appendix F. The discussion in this section leads to the following proposition:

***Proposition 2***

*When there are sufficient instantaneous decreasing returns to each R&D activity ((SC1) and (SC2) hold), the model is stable and the comparative static results of subsidies to R&D activity are as expected: a subsidy to innovative activity increases I, and a subsidy to imitative activity increases C. When there are not sufficient instantaneous decreasing returns to each R&D activity ((SC1) and ((SC2) don't hold), the model is unstable, and the comparative static results are reversed.*

## 2.4 Restrictions And An Example

### 2.4.1 Restrictions

Here I discuss the various parameter restrictions. It is shown in Segerstrom (1991) that $\lambda$ large enough and $\bar{L}$ small enough to satisfy Assumptions A1-A3 are required. In the previous section, $\theta \geq 1$ and $\phi \geq 2$ were shown to be sufficient for stability. There is one other inequality which must hold in the steady state for a well-behaved model. This restriction, (R1), must hold for $C > 0$, $I > 0$ (See Appendix D):

$$2 > \frac{a_I I^{\theta}}{a_C C^{\phi}} > 1 \ . \tag{R1}$$

This restriction implies that the model requires partial diffusion of product technology from innovators to imitators. It also limits the cost advantage that imitation has, relative to innovation. One way to ensure that (R1) holds is to assume that specific capital is mobile in the long run and that the economy is in long-run equilibrium at F in Figure 2.1. The return to capital will then be equalized across sectors, and there will be a relationship between the 'price' or expected benefit ratio, the wage/return to capital ratio, and the capital/labor ratios of the two activities, as described by the Samuelson diagram in Figure 2.4. Assume that $\bar{L}$ is the total labor available to R&D in the steady state and that innovation is capital intensive relative to imitation ($\gamma > \epsilon$). Then,

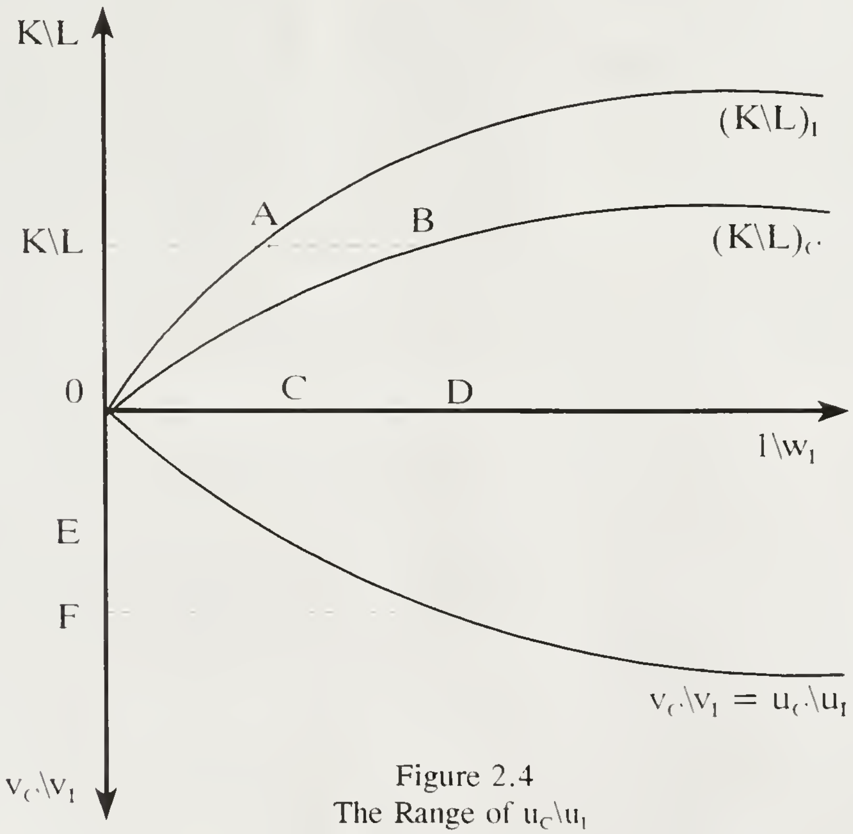


Figure 2.4
The Range of $u_C \backslash u_I$

$$\frac{u_I}{u_C} = \frac{\gamma}{\epsilon}\frac{A_C}{A_I}\frac{\left(\frac{K_I}{L_I}\right)^{\epsilon-1}}{\left(\frac{K_C}{L_C}\right)^{\gamma-1}} .$$

where $A_C$ and $A_I$ are the general coefficients of the Cobb-Douglas production functions for imitation and innovation, respectively, defined in Appendix B. By examination of Figure 2.4, it should be apparent that, for an appropriate choice of $\epsilon$, $\gamma$, $A_I$, and $A_C$ (which position the two functions in the top quadrant), choosing $\bar{K}$, the total economy endowment of capital, for given $\bar{L}$ (already restricted above), can limit the range of $u_I \backslash u_C$ (EF in Fig. 2.4).

### 2.4.2 Example

It remains to show an example in which (R1) holds and the model is well-behaved. Let $\bar{L} = 1$, $\bar{K} = 2$, $\epsilon = 1/4$, $\gamma = 1/3$, $A_C = 2$, $A_I = 1$, $\lambda = 4$, and $\rho = .05$. Then $\theta = 3$, satisfying (SC1) and $\phi = 2$, satisfying (SC2). Using the above and the Cobb-Douglas functions of Appendix B, the range of $w_I = w_C$ in the long run is (1, 1½), the range of $u_I$ is then (1.76, 2.378), and the range of $u_C$ is (.95, 1.238). Then the range of $u_I/u_C$ is (1.857, 1.921), satisfying (R1). Using (2.17) and (2.18), $C^* = 1.93$ and $I^* = .83$ when $w_I = w_C = 1$, and $C^* = 1.94$ and $I^* = .94$ when $w_I = w_C = 1½$. This is one example where all restrictions of the model are satisfied.

## 2.5 Conclusion

I have used Samuelson's Correspondence Principle to develop stability conditions for a generalized version of the Neo-Schumpeterian growth model of Segerstrom (1991).

Innovation and imitation are endogenously determined in a dynamic, zero-profit, general equilibrium model of growth in consumer utility through quality improvements. Each R&D activity uses labor and specific capital. Standard adjustment mechanisms, supported in principle by the work of Neary (1982), are used in the stability analysis. I show that sufficient instantaneous decreasing returns to scale in R&D are required for a well-behaved model in which the comparative static results are reasonable.

The implication for future work is that the inclusion of separate R&D sectors in a dynamic general equilibrium model with levels of R&D activity determined by free entry and zero-profit conditions imposes restrictions on the structure of the model. The mathematical sophistication of Segerstrom's model disguises the stability problem, but an appeal to Samuelson's analysis clarifies the issues.

# CHAPTER 3
# ENDOGENOUS INTERNATIONAL TECHNOLOGY TRANSFER AMONG ADVANCED COUNTRIES

## 3.1 Introduction

> *A photograph snapped at a fashion show in Milan can be faxed overnight to a Hong Kong factory, which can turn out a sample in a manner of hours. That sample can be fedexed back to a New York showroom the next day.*
>
> *Wall Street Journal 8-8-94*

Imitation of new products or processes is an increasingly important avenue of technology transfer in the global marketplace. In the U.S., it is estimated that sixty percent of patented innovations are imitated within four years.[1] Furthermore, among advanced countries, the rate of international technology transfer through imitation depends on R&D investment.[2] Finally, technology transfers flow in all directions among

[1]Mansfield et al. (1981), pg. 913. This paper investigates, through case studies, the magnitude and determinants of imitation costs and the relationship of these costs to innovation costs, the imitation time lag, patents, and entry.

[2]Mansfield et al. (1982), pg. 35. Based on data from 37 innovations in the plastics, semiconductors, and pharmaceutical industries, this study also concludes that imitation lags appear to be decreasing over time.

advanced countries.[3] Japan spends resources to copy U.S. technology in semiconductors and automobiles, but U.S. companies also try (with limited success) to transfer Japanese technology (i.e. quality circles) to the U.S.[4]

Several endogenous growth models include various aspects of the complex dynamics of imitation. First, Segerstrom, Anant and Dinopoulos (1990) and Dinopoulos, Oehmke and Segerstrom (1993) model imitation as an exogenous, certain and costless activity. These studies explore the effects of changes in the imitation lag on innovation and growth. Second, Grossman and Helpman (1991a) develop a model of North - South trade in which the South engages in endogenous imitation based on expected profits from lower manufacturing costs, which result in a lower wage. None of the models mentioned above endogenizes imitation among advanced countries with identical wages. Nor do any generate multidirectional patterns of endogenous international technology transfer.

To that end, this chapter develops a two-country model of growth based on the introduction of new products of higher quality. This model is closely related to that of Chapter 2. Endogenous innovation and endogenous imitation influence both consumer utility and trading patterns. To simplify the analysis, I assume that there is only one factor of production, labor. Instantaneous diminishing returns to R&D, essential for

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[3]See Eaton and Kortum (1994) and Coe and Helpman (1993). The first study, using data on patents, productivity, and research in five leading research economies, reports that, for each country, more than 50 percent of productivity growth is attributable to foreign technology. The second study, using data on 22 OECD countries, finds that international R&D spillovers to trading partners accounts for about one quarter of the total social return to the R&D investment of the seven largest OECD economies.

[4]Dinopoulos and Kreinin (1994) report that U.S. companies spent $950 billion, in the period 1983-1993, in an attempt to implement Japanese management techniques (p.2).

stability, are achieved through specific functional forms. A new element is the important role assumed by imitative activity in the ongoing global growth process. Imitative activity diffuses leading edge technology and keeps the industry competitive in R&D. The model is used to analyze the effects of differences in relative labor endowments on trading patterns and technology transfer. This analysis is conducted in an integrated global economy in which factor price equalization (FPE) prevails.

The results of the analysis can be summarized as follows. A unique, stable, integrated equilibrium is found to exist (Proposition 3), in which both innovation and imitation contribute to growth and welfare (Proposition 4). An increase in the world labor endowment increases the rates of innovation, imitation, and growth; a world subsidy to innovation (or imitation), increases the rate of innovation (or imitation) (Proposition 5). For a large set of endowments, the integrated equilibrium can be replicated, under factor price equalization, by trade in final goods, without direct foreign investment (DFI) or trade in R&D services (Proposition 6). Stochastic trade patterns with two-way international technology transfer and product cycles are generated for a wide range of endowments (Proposition 7).

The following pages set out the model and establish the global equilibrium (Section 3.2), examine welfare and growth (Section 3.3), discuss international technology transfer and trade patterns (Section 3.4); and look at the conclusions to be drawn from the analysis and elaborate implications for future research (Section 3.5).

## 3.2 World Economy

### 3.2.1 Overview

A representative agent maximizes utility over time and over a continuum of final goods subject to stochastic quality increments of fixed amount. Consumer savings are channeled through an asset market to firms investing in R&D. In each industry, firms 'buy' a probability of winning the race to discover the next (or copy the latest) quality level by engaging in costly innovative (or imitative) activity. There is free entry into each innovation (or imitation) race. The successful innovator captures the market through limit pricing and enjoys temporary monopoly profits until its product quality is imitated. Successful imitators duplicate the industry leader's product quality and collude with the quality leader to obtain temporary duopoly profits until the next innovation occurs in that industry.

Production of final goods exhibits CRS in labor, but requires knowledge of the current state of the art. There are instantaneous diminishing returns to aggregate industry R&D activity. Put differently, the probability of an innovation (or imitation) occurring is concave and increasing in the amount of resources devoted to innovative (or imitative) activity. Unit labor requirements in each R&D activity are endogenously determined.

In the steady state, world expenditures, levels of innovative and imitative activity per industry, and the percentage of monopoly industries are constant over time. Each industry is first targeted for innovation, and then, for imitative, races, so market structure fluctuates between monopoly and duopoly in stochastic cycles. The following

subsections describe consumer behavior, the product markets, R&D races, the labor market, and the existence of the integrated equilibrium.

3.2.2 Consumer Behavior

The representative world consumer maximizes an intertemporal utility function identical to that in Chapter 2, with a CDP instantaneous utility function. The usual static maximization problem yields

$$d_{ht}(\omega) = \frac{E(t)}{p_{ht}(\omega)} \tag{3.1}$$

as world industry demand at time t, where $h \equiv h_t(\omega)$ is the highest quality available at time t in industry $\omega$. E(t) is instantaneous expenditure, and $p_{ht}(\omega)$ is the price of good h at time t .

$$\frac{\dot{E}(t)}{E(t)} = r(t) - \rho \tag{3.2}$$

is the condition of intertemporal maximization, r(t) is the instantaneous interest rate which clears the asset market continuously, and $\rho$ is the subjective discount rate.

3.2.3 Product Markets

The current quality leader captures the market with a limit price determined by its degree of quality advantage, which is equal to $\lambda$, the quality increment over the previous quality. If labor is the numéraire, $p = \lambda$ in each industry at all times. A successful innovator becomes the sole producer in that industry and can earn monopoly profits of

$$\pi_L = (\lambda - 1)\left(\frac{E(t)}{\lambda}\right) = \left(1 - \frac{1}{\lambda}\right)E(t) , \tag{3.3}$$

where $(\lambda\text{-}1)$ is the markup and $E(t)/\lambda$ is industry demand. Industries in which there is a single producer are denoted as $\alpha$-industries. When this new quality is imitated, the

winner of that race can collude with the current leader. They charge $p = \lambda$, split the market, and each earn

$$\pi_C = \left(1 - \frac{1}{\lambda}\right)\frac{E(t)}{2} \quad . \tag{3.4}$$

Industries with two producers are denoted as $\beta$-industries.

<u>3.2.4 Innovative R&D</u>

Innovative R&D activity occurs only in duopoly, $\beta$, industries in which diffusion of the current state-of-the-art technology through imitation is complete.[5] By engaging in i units of innovative activity in industry $\omega$, a firm buys the probability idt of successfully carrying out the next innovation in the industry in interval dt. The arrival rate of innovations is a Poisson process, and the time duration of each innovation race is exponentially distributed. Aggregate industry innovative activity, I, is the mean rate of occurrence of innovations. Idt is the probability that if the innovation hasn't occurred by time t, it will by time t+dt.

The firm's level of innovative activity can be related to the amount of labor it hires:

$$i = \frac{l_I}{(a_I + b_I L_I)} \; .$$

The variable $l_I$ is the amount of labor hired by a firm engaged in innovation; $L_I$ is aggregate industry employment in innovation; $a_I$ is the minimum unit labor costs of innovative R&D. The variable $b_I$ measures the degree to which the level of industry innovative activity lowers the individual firm's labor productivity.

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[5]It is assumed that the whole industry (not just the monopolist) must be on the technology frontier before it can engage in innovation. This is discussed in more detail below.

Aggregate innovative activity in each industry targeted for innovation is given by

$$I = \frac{L_I}{(a_I - b_I L_I)} \,. \tag{3.5}$$

The aggregate industry probability of success is a concave function of industry labor employed in innovation. A possible source of instantaneous diminishing returns to innovative R&D is a negative externality associated with rising industry innovative activity. The increased possibility of parallel research programs reduces the effectiveness of additional R&D activity in quickening the pace of innovation.[6] Substituting from (3.5) for $L_I$, unit labor requirements (and unit costs when $w=1$) for innovation are

$$u_I = \frac{L_I}{I} = a_I + b_I L_I = \frac{a_I}{(1 - b_I I)} \,. \tag{3.6}$$

Innovative activity is subject to diminishing returns at the industry level, but individual firms regard costs as constant since they take $L_I$ and I as given.

<u>3.2.5 Imitative R&D</u>

Imitative activity plays an important implicit role in this model. Through an exogenous effect occurring at the end of each R&D race, the imitation process lowers the minimum unit costs of engaging in the next innovation race. This may occur because of experience gained in conducting R&D.[7] Imitative activity is modeled in a parallel

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[6]Stokey (1992) makes this same argument for instantaneous diminishing returns to R&D.

[7]It is assumed that these effects are large enough that innovation never occurs in an $\alpha$-industry. In monopoly, $\alpha$, industries, minimum unit labor costs are assumed to be $a_{ID}$, where $a_{ID} > a_I$. We can assume that $a_{ID} \rightarrow \infty$. Since this is a model which considers large innovations, as is pointed out below, this is like saying that at the time of the introduction of black and white TV, color was not an immediate possibility.

fashion to innovative activity. By engaging in c units of imitative activity in an industry targeted for imitation, a firm buys the probability cdt of successfully copying the current state-of-the-art quality in that industry in interval dt. The arrival rate of imitations is a Poisson process and the time duration of each imitation race is exponentially distributed. Aggregate industry imitative activity, C, is the mean rate of occurrence of imitations. Cdt is the probability that the imitation occurs in interval dt.

Aggregate imitative activity in each industry targeted for imitation is

$$C = \frac{L_C}{(a_C + b_C L_C)} . \tag{3.7}$$

The term $L_C$ is aggregate industry employment in imitation; $a_C$ is the minimum unit labor costs of imitative R&D; $b_C$ measures the degree to which the level of industry imitative activity lowers the individual firm's labor productivity. The aggregate industry probability of success is a concave function of industry labor employed in imitation. The source of diminishing returns to imitative R&D is also a negative externality associated with rising industry imitative activity. Substituting from (3.7) for $L_C$, unit labor requirements (and unit costs when w=1) for imitation are

$$u_C = \frac{L_C}{C} = a_C + b_C L_C = \frac{a_C}{(1 - b_C C)} . \tag{3.8}$$

Imitative activity is subject to diminishing returns at the industry level, but individual firms view unit costs as constant by taking $L_C$ and C as given.

3.2.6 Labor Market

The competitive labor market clears at all times. The full-employment condition is

$$\bar{L} = \frac{E(t)}{\lambda} + u_I \beta(t) I + u_C \alpha(t) C . \tag{3.9}$$

The term $\bar{L}$ is the total world endowment of labor: $E/\lambda$ is the labor required to produce final goods: $u_I$ and $u_C$ are the labor requirements in innovation and imitation respectively, as defined in (3.6) and (3.8). The term $\beta$ is the proportion of industries undergoing innovation, and I is the per industry level of innovation. Hence, $\beta I$ is world innovative activity. Also, because $\alpha$ is the proportion of industries undergoing imitation, and C is the per industry level of imitative activity, $\alpha C$ is world imitative activity.

3.2.7 Industrial Targeting

The evolution of industries with one quality leader is

$$\dot{\alpha}(t) = (1 - \alpha(t))I - \alpha(t)C \ . \qquad (3.10)$$

When $\dot{\alpha}(t) = 0$, as it does in the steady state,

$$\alpha = \frac{I}{I+C} \quad , \quad \beta = \frac{C}{I+C} \ . \qquad (3.11)$$

These equations are identical to (2.12) and (2.13), in section 2.2.3.2.

3.2.8 Steady-State Equilibrium

The steady state is assumed to be one in which world consumer expenditure flows, E, and the proportion of industries with one quality leader, $\alpha$, are constant over time, and I (or C) is constant across all $\beta$ (or $\alpha$) industries and time. Under these assumptions, a symmetric Nash equilibrium steady state exists with the following characteristics: the instantaneous interest rate equals the subjective discount rate ($r(t) = \rho$). No R&D is conducted by current monopolists or duopolists. Only duopoly ($\beta$) industries are targeted for innovation races, and only monopoly ($\alpha$) industries are targeted for imitation. Thus, I (or C) is zero in all $\alpha$ (or $\beta$) industries. There are only two types of market structure--monopoly and duopoly. This is because, due to parameter

restrictions made for ease of analysis, collusion is only supportable between the innovator and one imitator. There is one winner of any given imitation race. Each industry follows a stochastic sequence of alternating periods of innovation followed by imitation, as it climbs up its quality ladder.

There are two types of intraindustry intertemporal R&D spillovers in the steady state. There are endogenous spillovers from innovation to imitation. In equilibrium, unit costs of imitation are lower than unit costs of innovation. The same probability of success in interval dt can be purchased for less in an imitation race. This type of spillover can arise when innovators cannot appropriate all of the knowledge associated with their product. Some knowledge may be embodied in the product, for example.

The second (exogenous) type of intertemporal R&D spillover, from one product cycle to the next, is captured by the assumption that the minimum unit costs of innovation, $a_I$, are constant over time, even though each innovation is more valuable than the previous one. In models with innovation only, this characteristic of the model is explained as the result of exogenous spillovers of knowledge, whereby current competitors in an innovation race can effortlessly acquire all information pertinent to the previous innovation, which assists their efforts in the current race. This interpretation doesn't make sense, however, in a model in which an industry makes imitative R&D expenditures expressly to learn current technology.

In fact, though still exogenous, these spillovers can be interpreted as working through the imitation process. The imitation process diffuses the current state-of-the-art throughout the industry, and increases industry experience in R&D. If the second effect

is large, as is assumed, even the industry leader will not engage in innovative activity prior to imitation. So, it may be that there are spillovers of knowledge from previous innovations, but these are not completely disembodied. They are associated with imitative R&D activity and can be interpreted as a by-product of the competitive race for collusive profits. Assume that the industry in general moves close enough to the technology frontier and gains enough R&D experience, as a consequence of the imitation race, to engage in the next innovation race at minimum unit costs $a_I$. By assumption, the costs of carrying out the next innovation are prohibitively high until after imitation of the current quality has occurred and the information obtained has substantially increased the productivity of labor engaged in the next innovation race.

Let $a_{ID}$ denote the minimum unit costs (labor requirements) of innovation in an $\alpha$-industry. The assumption is that

$$a_{ID} > \frac{3(\lambda - 1)\bar{L}}{\rho} . \qquad \textbf{Assumption A4}$$

Assumption A4 states that unit labor requirements for innovation <u>in an $\alpha$-industry</u> are so high, relative to the world endowment of labor, that innovative activity never occurs in an $\alpha$-industry. The unit costs of the innovation race to discover the $j+1^{th}$ quality are $a_{ID}$ during the monopoly stage of quality j, but fall to $a_I$ as a result of experience gained in R&D activity associated with the duplication of quality j. These effects are exogenous and symmetric across industries. This characteristic leads to the cyclical nature of the market structure in which, in each industry, each innovation must be imitated before research can begin to discovery its replacement.

Under free entry, zero-profit conditions (ZPC), which govern the level of innovation and imitation, equate expected discounted rewards to expected costs. The ZPC's in each industry are, for innovation,

$$v_I \equiv \frac{\pi_L + C\, v_C}{\rho + C} = u_I = \frac{a_I}{1 - b_I I} \, . \tag{3.12}$$

and for imitation,

$$v_C \equiv \frac{\pi_C}{(\rho + I)} = u_C = \frac{a_C}{1 - b_C C} \, . \tag{3.13}$$

Part of $v_I$, the expected discounted reward to innovation, are dominant profit flows, $\pi_L$. The other part of $v_I$ represents the expected value of collusive profit flows. Expected discounted benefits to imitation, $v_C$, are collusive profits discounted by the instantaneous interest rate, $r(t) = \rho$, plus the probability of subsequent innovation in that industry, I, which represents the probability that the flow of profits will stop. $v_C$ also represents expected discounted benefits to the innovator after imitation occurs. Since C is the mean rate of occurrence of imitations, $Cv_C$ is the expected value of collusive profit flows to the innovator. All benefit streams to the innovator are discounted by the subjective discount rate and the threat of imitation. By no arbitrage conditions in the asset market, $v_I$ and $v_C$ are also the firm values of successful innovators and imitators. [8]

The model can be reduced to the endogenous determination of $I^*$ and $C^*$ (* denotes a steady state value). How these change over time, out of the steady state, determine how E(t) and $\alpha(t)$ evolve over time. In the steady state, I, C, E and $\alpha$ are constant. Assume that

$$\dot{I} = \Psi(v_I - u_I) \tag{3.14}$$

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[8]See Dinopoulos (1994).

and

$$\dot{C} = \Phi(v_C - u_C) \; . \tag{3.15}$$

where $\Psi'$ and $\Phi'$ are greater than zero and $\Psi(0) = \Phi(0) = 0$ (looking at (3.13), it is apparent that $\dot{I} = 0$ and $\dot{C} = 0$ imply $\dot{\alpha} = 0$ ). Substituting into (3.14) from (3.3), (3.4), (3.6), (3.8), (3.9), (3.11), (3.12), and (3.13); and letting $\dot{I} = 0$, as in the steady state,

$$\frac{(\lambda - 1)}{2}\left[\bar{L} - \frac{IC}{1+C}\left(\frac{a_I}{1-b_I I} + \frac{a_C}{1-b_C C}\right)\right] = \frac{(\rho+1)(\rho+C)a_I}{(2(\rho+1)+C)(1-b_I I)} \; . \tag{3.16}$$

Substituting into (3.15) from (3.4), (3.6), (3.8), (3.9), (3.11), and (3.13); and letting $\dot{C} = 0$,

$$\frac{(\lambda - 1)}{2}\left[\bar{L} - \frac{IC}{1+C}\left(\frac{a_I}{1-b_I I} + \frac{a_C}{1-b_C C}\right)\right] = (\rho+1)\left(\frac{a_C}{1-b_C C}\right) \; . \tag{3.17}$$

Finally, combining (3.3), (3.4), (3.12), and (3.13) gives a steady-state zero-profit condition:

$$\frac{a_I}{(1-b_I I)} = \frac{2(\rho+1)+C}{(\rho+C)}\,\frac{a_C}{(1-b_C C)} \; . \tag{3.18}$$

Note that, using (3.6) and (3.8), $u_I/u_C$ is always greater than one in the steady state by (3.18). So, there are spillovers from innovation to imitation, the magnitude of which are endogenously determined. These R&D spillovers must exist for imitation to be profitable relative to innovation since gross returns to innovation are greater.

Equations (3.16), (3.17) and (3.18) can be graphed as in Figure 3.1 where $I_1 < I_0$ and $C_1 > C_0$ if

$$2a_I\rho > (\lambda - 1)\bar{L} > \max\{a_I\rho \, , \, 1\} \; , \qquad \textbf{Assumption A5}$$

$$a_I / a_C \geq 2, \qquad \textbf{Assumption A6}$$

$$b_I > \max\left\{a_I \, , \, \frac{1}{\rho}\right\} \; , \text{ and } \quad b_C > \frac{1}{\rho} \; . \qquad \textbf{Assumption A7}$$

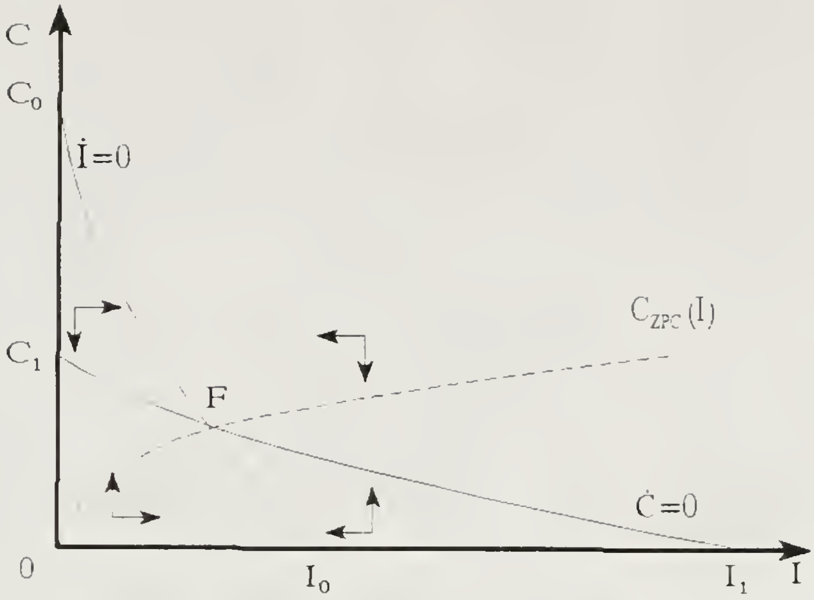


Figure 3.1
Equilibrium

Assumption A5 requires that the world labor force be large enough to support innovation but not too large. Assumption A6 is consistent with innovation being more expensive than imitation. Assumption A7 gives the stability conditions which guarantee that $\dot{I} = 0$ cuts $\dot{C} = 0$ from above. Given Assumptions A1 - A7,

***Proposition 3***

*The Nash equilibrium steady state represented in Figure 3.1 exists and is unique and stable.*

Proof: See Appendix D for the properties of (3.16), (3.17), and (3.18), which, when graphed in Figure 3.1, shows F to be a unique equilibrium. F is shown to be a stable equilibrium in Appendix E.

## 3.3 Welfare and Comparative Statics

Appendix G shows that the world representative agent enjoys a certain and continuous growth rate in steady-state expected utility of

$$g^{*} = \frac{I^{*}C^{*}\ln\lambda}{I^{*}+C^{*}} = \frac{1}{(1/I^{*})+(1/C^{*})}\ln\lambda \ . \tag{3.19}$$

and steady-state expected discounted welfare of

$$U = \frac{1}{\rho}\left(\ln\left(\frac{E^{*}}{\lambda}\right) + \frac{g^{*}}{\rho}\right) . \tag{3.20}$$

Both innovation and imitation influence growth, and both growth and current expenditures affect welfare. Equation 3.20 is not surprising in a dynamic model. Equation 3.19, however, is unusual in that imitation contributes positively to growth for a given level of I, as is clear from the discussion of Assumption A4. Each quality level must go through a period of innovation followed by imitation. In equation (3.19), 1/I and 1/C are the expected durations of innovation and imitation races respectively. 1/I + 1/C is, therefore, the expected duration of R&D activity associated with each quality level which must occur before the next cycle can begin.

Appendix G shows that, given Assumption A4 and

$$b_I = 2b_C \ . \qquad \textbf{Assumption A8}$$

the following is true:

***Proposition 4***

*The welfare maximizing levels of innovation and imitation are positive.*

Assumption A8 is probably more restrictive than necessary, but simplifies the algebra. Nethertheless, it captures the notion that innovation is more difficult than imitation. Proposition 4 occurs because diffusion through imitation is a necessary part of the ongoing growth. This is an interesting result because it embodies a positive role for imitation that operates through the production side. Any positive effects of imitation are usually thought to occur because of either product differentiation or increased competition.[9]

Before leaving the discussion of growth and welfare, and as a prelude to the discussion of trade patterns, it is useful to note the effect of an increase in the size of the economy on the rate of growth and welfare. An increase in $\bar{L}$ shifts both curves out in Figure 3.1 but leaves $C_{ZPC}$ unchanged (see (3.16), (3.17) and (3.18)). Therefore, $I^*$ and $C^*$ increase, which increases the growth rate for a given level of expenditure. World welfare rises. This demonstrates the economies of scale characteristic of these models when R&D expenditures are spread over larger markets. The potential for gains from integration exists. The comparative static results of subsidies to innovation and imitation are also given in Proposition 5:

***Proposition 5***

*(i) An increase in the world labor endowment increases innovative activity, imitative activity, growth and welfare.*

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[9]See Dinopoulos (1992) and Davidson and Segerstrom (1994) for examples of these two effects. There is a substantial partial equilibrium literature that studies the contribution of imitation to diffusion of technology. See Baldwin and Scott (1987) for a survey of this literature and Cohen and Levinthal (1989) for a general equilibrium treatment of this effect.

*(ii) An increase in a per unit subsidy to innovative activity increases innovative activity.*

*(iii) An increase in a per unit subsidy to imitative activity increases imitative activity.*

Proof: (i) is discussed above. (ii) and (iii) are discussed in Appendix F.

## 3.4 Trade and Technology Transfer

The technique used to analyze trade patterns is the integrated equilibrium approach employed by Helpman and Krugman (1993). The integrated equilibrium, established in Proposition 1 and indicated by F in Figure 3.1, represents the world allocation of resources when labor is perfectly mobile. This section analyzes trade patterns that can occur when free trade, between two countries with immobile labor, replicates the integrated equilibrium and the wage rate is equalized. International technology transfer, through imitation, influences these trade patterns. The extent of these technology transfers is governed by relative national labor endowments. The first subsection explores the assumptions that shape the trading environment and derives the labor constraints for each country and the trade balance. The next subsection looks at the conditions under which the wage rate is equal across countries. Finally, the trade and technology transfer patterns that can occur in the replicated integrated equilibrium are discussed.

### 3.4.1 Assumptions/Trading Framework

The following **Assumptions** are made: **A9** Technology cannot be transferred costlessly between firms or across borders. **A10** Labor is not internationally mobile.

**A11** Financial capital is internationally mobile. **A12** Each country targets all $\alpha$ (or $\beta$) industries equally for imitation (or innovation). **A13** Each country's share of assets equals its share of world labor. **A14** The percentage of monopoly and duopoly industries in each country is constant over time in the steady state. **A15** Each country's expenditures are constant across time in the steady state. **A16** R&D and final goods production technologies are identical across countries as is the magnitude of quality increments. **A17** Trade is frictionless and unimpeded. **A18** Each country's representative agent has the same homothetic CDP utility.

Assumption A9 is consistent with the evidence.[10] DFI occurs when foreign firms conduct either innovative or imitative R&D in the home country or when home firms conduct R&D in foreign countries, but only imitative R&D represents the <u>costly</u> transfer of technology. Since R&D technologies are identical across countries and market share and profits are independent of both country of production and country of ownership, there is no motive for DFI <u>when the wage rate is equalized</u>. Thus, it is assumed that there are no multinationals. Licensing, one firm selling the rights of production to another, is possible but would involve some learning expenditures of uncertain length and effectiveness. Licensing is, therefore, compatible with costly imitation, but is not considered. Trade in R&D services is assumed not to occur, either through DFI or licensing. Furthermore, there are no (intermediate or capital) traded goods that might

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[10]See Baldwin and Scott (1987), Ch. 4, which surveys the theoretical literature and empirical evidence on the diffusion of innovations. A general conclusion is that "the transfer of technical information is rarely, if ever, costless; and it may be risky as well" (p. 116).

embody technology. *Therefore, each country must invest its own resources in and win R&D races to participate in final goods production.*

The labor constraints can now be constructed. Let subscripts H and F denote Home and Foreign variables. Let $\sigma$ denote Home's proportion of the labor endowment. Then,

$$\bar{L}_H = \sigma\bar{L} \quad . \tag{3.21}$$

Define $\alpha_H$ as the proportion of dominant firms in Home, $\beta_H$ as the proportion of duopolies based totally in Home, and $\bar{\beta}$ as the proportion of duopolies in which one duopolist resides in each country. Let s be the fraction of final goods manufactured in Home. Then

$$s = \alpha_H + \beta_H + \bar{\beta}/2 \quad . \tag{3.22}$$

The Home and Foreign labor constraints are, considering Assumption A12 and using Equation 3.22,

$$\bar{L}_H = s\frac{E}{\lambda} + \beta L_{IH} + \alpha L_{CH} \tag{3.23}$$

and

$$\bar{L}_F = (1-s)\frac{E}{\lambda} + \beta L_{IF} + \alpha L_{CF} \quad , \tag{3.24}$$

where $L_{IH} + L_{IF} = L_I$ is total labor employed in innovation, and $L_{CH} + L_{CF} = L_C$ is total labor employed in imitation.

Consider Home's share of manufacturing. Assumptions A12 and A14 imply that $\dot{\alpha}_H = \beta I_H dt - \alpha_H C dt = 0$ . This, together with (3.11), implies that

$$\alpha_H = \frac{I_H}{I^* + C^*} = \frac{I_H}{I^*}\alpha \quad . \tag{3.25}$$

The same assumptions imply that $\dot{\beta}_H = \alpha_H C_H - \beta_H I^* = 0$ , or

$$\beta_H = \frac{C_H}{C^*}\frac{I_H}{I^*}\beta \ . \tag{3.26}$$

Since $\dot{\beta} = \dot{\beta}_H + \dot{\beta}_F = 0$ , it follows that $\bar{\beta} = \alpha_F C_H + \alpha_H C_F - \bar{\beta} I^* = 0$ , or

$$\bar{\beta} = \alpha_F \frac{C_H}{I^*} + \alpha_H \frac{C_F}{I^*} \ . \tag{3.27}$$

All this implies that

$$\beta_H + \bar{\beta}/2 = \frac{1}{2}\left(\frac{C_H}{C^*} + \frac{I_H}{I^*}\right)\beta \ . \tag{3.28}$$

These equations are easily interpreted. Recall that there is no trade in R&D services so that all production within a country is due to R&D carried out in that country. Then s and (1-s) are determined by the relative amounts of R&D done in each country. For example, if Home does one half of the world innovative R&D, by the Law of Large Numbers, it will win one half of innovation races and, in the steady state, will have one half of all dominant firms. If Home also does one half of all world imitative R&D, it will have one half of all duopoly industry firms. Home would then have one half of all manufacturing production.

Turn next to the trade balance. Since each consumer is completely diversified, each will own a share of each successful firm in the exact proportion to her share of world assets. Given international financial capital mobility, consumer intertemporal maximization, and $\dot{E}_H = \dot{E}_F = \dot{E} = 0$ then, $r = r_H = r_F = \rho$ in the steady state. Let $Y = Y_H + Y_F$ be the total value of world assets, in the steady state, made up of assets held by the Home and Foreign agents respectively. Let $V_H$ be the total value of Home firms:

$$V_H = \alpha_H v_I + (\beta_H + \bar{\beta}/2)v_C \ . \tag{3.29}$$

Then, $Y = V = V_H + V_F = \alpha v_I + \beta v_C$. Y must be constant by Assumption A15. Since E, I, and C are constant, $v_I$ and $v_C$ are also constant (See (3.3), (3.4), (3.12), (3.13)). Since $\dot{\alpha} = \dot{\alpha}_H = \dot{\alpha}_F = 0$, by Assumption A14, $V_H$ and $V_F$ are constant. Note that, by Assumption A13, Home's share of world assets is equal to its share of labor. Then, $Y_H = \sigma Y = \sigma V_H + \sigma V_F$ and $Y_F = (1-\sigma)V_H + (1-\sigma)V_F$. Since there is no trade in assets, the current account must balance:

$$s\frac{E_F}{\lambda} - (1-s)\frac{E_H}{\lambda} + \sigma\rho V_F - (1-\sigma)\rho V_H = 0 \,. \tag{3.30}$$

The first term is Home exports: the second is Home imports. Their difference represents the merchandise trade balance. The third term, Home's interest receipts, less the last term, Home's interest payments, is the service account.

3.4.2 Factor Price Equalization Set

The FPE set, or set of relative national labor endowments which can reproduce the integrated equilibrium, can now be derived. In this model, FPE will always hold if both countries engage in R&D activity. Because of integration of final goods markets (which implies a single global innovation race with a single winner) and the nature of the externality associated with R&D activity, world labor employed in innovation (or imitation) determines firm and industry unit labor requirements at home and abroad.[11] Unit labor requirements are endogenous, but are always equal across countries in each

[11]If a different, country-specific, source of instantaneous diminishing returns to R&D (such as immobile specific factors) is assumed, then a wage differential can occur which, if large enough, will lead to a collapse of the collusive equilibrium. The model would then revert to a North-South model.

R&D activity, and also in final goods production, by Assumption A16. Countries cannot specialize in production, however, <u>without</u> incurring R&D expenses, by Assumption A9.

Because specialization is impossible, the wages in each country must be equal. Suppose that the wage in Home, $w_H$, is higher than the wage in Foreign, $w_F$. Unit costs of both R&D activities will be greater at Home ($u_I^* w_H > u_I^* w_F$, $u_C^* w_H > u_C^* w_F$).[12] Similarly, since marginal costs of final goods production are higher at Home ($w_H > w_F$), profits and expected discounted benefits to either R&D activity will be lower at Home. By financial capital mobility, funds would flow to Foreign R&D races, bidding up wages there and lowering wages at Home. Labor mobility within each country, and trade and financial capital mobility between countries, equalizes wages. Consequently, as long as each country has a sufficient relative endowment of labor to acquire production through innovative R&D at $u_I^*$, imitative R&D at $u_C^*$, or both, the integrated equilibrium can be reproduced by trade under FPE.

Defining the FPE set is a matter of determining what the minimum share of labor is for each country to engage in R&D and the associated production. Because each country is assumed to engage in innovation in all $\beta$ industries, and imitation in all $\alpha$ industries, and because each country must engage in production of final goods for every race it wins, there is a minimum labor endowment below which the country cannot carry out these activities. For any endowment point that allocates a share of labor less than

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[12] $u_I^*$ and $u_C^*$ are the global integrated equilibrium steady state unit labor requirements in innovation and imitation respectively.

this minimum to either country, the integrated equilibrium will not be reproduced by trade under FPE.

The FPE set is represented graphically in Figure 3.2. Let the total length of the line be $\bar{L}$. The Home country's share of labor increases as the endowment point moves to the right. The Foreign country's share increases as it moves to the left. The point labelled $\bar{L}_H^M$ represents the endowment point for which Home's share of labor is at the minimum necessary to sustain production through innovation or imitation, whichever requires less labor at the margin in the integrated equilibrium. The point labelled $\bar{L}_F^M$

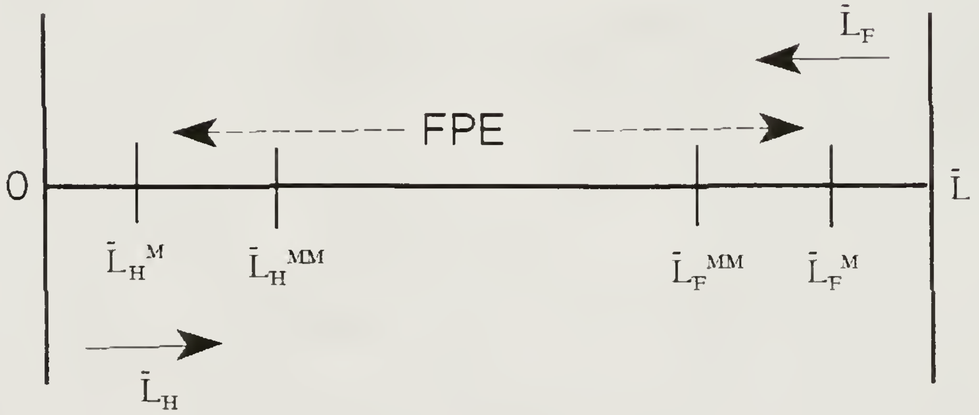


Figure 3.2
Factor Price Equalization Set

represents the same for the Foreign country. Hence, in the regions $(0, \bar{L}_H^M)$ and $(\bar{L}_F, \bar{L})$, FPE cannot be maintained by trade *under the assumptions outlined above.*

In the first region, Home is too small: in the second, Foreign is too small.[13] Therefore, $\bar{L}_H^M$, $\bar{L}_F^M$ is the set of endowment points for which both countries are large enough to conduct R&D at $u_I^*$ and $u_C^*$ and carry out the associated production. FPE must occur through trade, and the integrated equilibrium will be reproduced. The results of this section are summarized in Proposition 6:

***Proposition 6***

*If the distribution of labor endowments lies in the region* $\bar{L}_H^M$, $\bar{L}_F^M$ *in Figure 3.2, the integrated equilibrium, represented by F in Figure 3.1, can be achieved by balanced trade, between similar countries, in which there is no DFI or trade in R&D services.*

3.4.3 Trade Patterns

Having defined the FPE set, it is now convenient to turn to the characterization of trade patterns that can occur when the endowment point is in the FPE set. It is possible to get an expression relating Home's endowment of labor to Home's labor allocations across activities in a way consistent with the allocations in the integrated equilibrium. Assume that $\bar{L}$, the total world endowment of labor, satisfies Assumption A6, and the endowment point is in the FPE set. Relaxing the normalization on labor so

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[13]These minimum endowment points are derived in the Appendix H. It should be noted that, because each industry is of measure zero, if Assumption A13 is relaxed so that a country can target a selected set of industries for R&D, FPE will occur for all possible endowments. However, almost any alternative to Assumption A13 will render the model either more complicated or less interesting. A relaxation of Assumption A10, so that multinationals can costlessly transfer production abroad, will also assure FPE for all possible endowment points, but that would be contrary to the evidence. Neither of these points will be pursued further because trade patterns are only analyzed within the FPE set.

that demand for labor in Home production is $\frac{E}{\lambda w_H}$ per industry; using (3.3), (3.4), (3.12) and (3.13) in (3.23) and (3.24); solving for $w_H$ and $w_F$; and setting them equal gives, after some manipulation,

$$(s\bar{L} - \bar{L}_H) = (s - \sigma)\bar{L} = \beta'(sL_I - L_{IH}) + \alpha'(sL_C - L_{CH}) \quad . \tag{3.31}$$

This equation summarizes the patterns of labor employment at Home that are consistent with FPE. If the world economy can be represented by an integrated equilibrium in which each country faces the same prices and techniques of production, this equation must be satisfied. The special case, discussed below, will make it clear that this set is not empty. From (3.31) alone, under factor price equalization, there are multiple possible allocations of labor across activities in each country. Therefore, the pattern of trade is indeterminant.

Nethertheless, additional assumptions will uncover the rich patterns of trade possible in this model. Refer back to Figure 3.2. $\bar{L}_H^{MM}$ is defined as the minimum labor endowment point below which the home country is too small to conduct <u>both</u> innovation and imitation, and the associated production of final goods. $\bar{L}_F^{MM}$ is defined in a similar fashion for the Foreign country. If the endowment point falls within $(\bar{L}_H^{MM}, \bar{L}_F^{MM})$, both countries can engage in both types of R&D activity and the associated production of final goods.

Assume that the endowment point is in the region $(\bar{L}_H^{MM}, \bar{L}_F^{MM})$. Also assume symmetric labor activity. The two countries employ labor in each activity equal, in proportion, to their relative labor supply. Then, $L_{IH} = \sigma L_I$ and $L_{CH} = \sigma L_C$, which implies that $I_H = \sigma I$ and $C_H = \sigma C$. So, from (3.25), $\alpha_H = \sigma\alpha$; from (3.28),

$(\beta_H + \bar{\beta}/2) = \sigma\beta$; and from (3.22), $s = \sigma$; so that $sL_I = L_{IH}$ and $sL_C = L_{CH}$. Refer to Figure 3.3 for a graphical representation. The top parallel line represents the allocation of labor to final goods production, $L_P^* = E/\lambda$, innovative activity, $L_I^*$, and

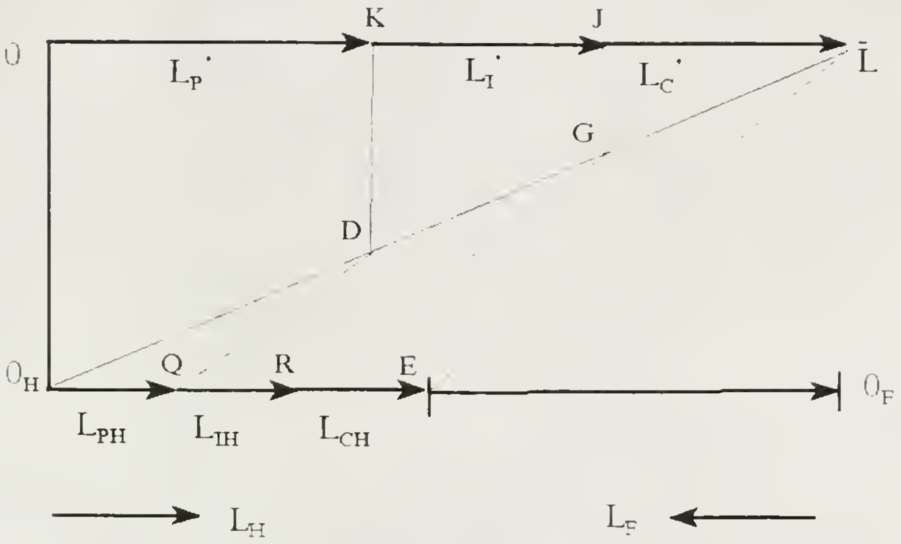


Figure 3.3
Symmetric Case

imitative activity, $L_C^*$, in the integrated equilibrium. The bottom parallel line represents the set of endowment points. $O_H$ is Home's origin; $O_F$ is Foreign's origin. For any endowment point, E, $O_HE$ is Home's endowment of labor, and $EO_F$ is Foreign's endowment. A diagonal line is drawn from $O_H$ to $\bar{L}$ and from E to $\bar{L}$. Dropping perpendicular lines from K and J to diagonal $O_H\bar{L}$ forms similar triangles $GJ\bar{L}$, $DK\bar{L}$ and $O_HO\bar{L}$, which makes $G\bar{L}/O_H\bar{L} = J\bar{L}/O\bar{L}$, $DG/O_H\bar{L} = KJ/O\bar{L}$, and $O_HD/O_H\bar{L} = OK/O\bar{L}$. Similar triangles $O_H\bar{L}E$, $O_HGR$, and $O_HDQ$ are formed by dropping lines parallel to $\bar{L}E$ from D and G to $O_HO_F$. $L_{PH}$, $L_{IH}$ and $L_{CH}$ are the allocations of labor to final goods

production, innovative activity and imitative activity respectively. By the properties of similar triangles, $L_{PH}/L_P^* = L_{IH}/L_I^* = L_{CH}/L_C^* = O_HE/O\bar{L} = \sigma$. A similar diagram can be constructed for the foreign country.

In addition to lending itself to convenient graphical representation, this symmetric case also simplifies the trade balance. With $\dot{E}_H = 0$ and $w = 1$,

$$E_H = L_H + \sigma\rho Y = \sigma(\bar{L} + \rho Y) \tag{3.32}$$

is expenditure at home. Also, $V_H = \sigma\alpha v_I + \sigma\beta v_C = \sigma V$, and the service account must balance (see equation 3.29). The shares of Home and Foreign expenditures, assets, labor in imitative and innovative activities and in manufacturing are equal to their shares in labor. So $s = \sigma$ and $(1-s) = (1-\sigma)$. Equation 3.30 becomes

$$s\frac{E_F}{\lambda} = (1-s)\frac{E_H}{\lambda} \Rightarrow \sigma(1-\sigma)\frac{E}{\lambda} = (1-\sigma)\sigma\frac{E}{\lambda} . \tag{3.33}$$

The merchandise trade account must balance if Home's proportion of manufacturing is equal to its proportion of assets, which is equal to its proportion of labor.

In this symmetric integrated equilibrium, Home will export from $\alpha_H$, $\beta_H$ (and $\bar{\beta}$ industries if $E_H < E_F$ or $\sigma < ½$). It will import from $\alpha_F$ and $\beta_F$ industries. Thus, this model generates product cycles among different sized countries. For example, suppose that an industry is dominated by a Home monopolist so that Home initially exports from this industry. Suppose that a Foreign firm successfully imitates this monopolist's quality. The Home and Foreign firms split the world market. If $\sigma$ is greater than one half, Home will now import in this industry. Another industry may not experience product cycles. A Home monopolist may be imitated by a domestic firm so that Home continues to dominate and export from this industry. In still another industry, say a duopoly based

wholly at Home, a Foreign firm may capture the entire market share through innovation. Consequently, Home may go from exporting to importing in that industry and may also recapture some of the market through imitation.

In general, Home and Foreign market shares fluctuate across industries. $\alpha_H C_F dt$ Home monopolists lose half their market shares to Foreign imitators in dt, and $\alpha_F C_H dt$ Foreign monopolists lose half their market shares to Home imitators. Also, $2(\beta_H + \bar{\beta}/2)I_F dt$ Home duopolists lose their total market shares to Foreign innovators, and $2(\beta_F + \bar{\beta}/2)I_H dt$ Foreign duopolists lose their total market shares to Home innovators. The pattern of trade fluctuates and has richer possibilities than a model of endogenous innovation alone. In particular, it is possible, in this model, for a country to capture part or all of the market in some industry and lose part or all of the market in other industries during the same period.

In each interval, dt, Foreign imitators successfully transfer technology from $\alpha_H C_F dt = \sigma(1-\sigma)\alpha^* C^* dt$ Home monopolists, and Home successfully transfers technology from Foreign monopolists in $\alpha_F C_H dt = (1-\sigma)\sigma\alpha^* C^* dt$ industries. In the symmetric case, these transfers are equal. Let $\tilde{\beta}_H$ ( $\tilde{\beta}_F$ ) be the proportion of duopoly industries in which Home (or Foreign) has successfully transferred technology from a Foreign (or Home) monopoly. Then,

$$\tilde{\beta}_H = \alpha_F C_H - \tilde{\beta}_H I^* \quad \rightarrow \quad \tilde{\beta}_H = (1-\sigma)\sigma\beta^* = (1-\sigma)\sigma\frac{C^*}{I^*+C^*}. \tag{3.34}$$

A similar calculation gives $\tilde{\beta}_F = \sigma(1-\sigma)\beta^*$, and $\bar{\beta} = \tilde{\beta}_H + \tilde{\beta}_F$. The transfer of technology from Home to Foreign (and vice versa), and the associated transfer of market share, are related to the global intensities of imitative and innovative activity. For given

levels of $I^*$ and $C^*$, the endowments of labor endogenously determine the extent of technology transfer. $\sigma = ½$ maximizes these transfers. Intuitively, the more equally endowed the two countries, the more they interact.

***Proposition 7***

*The pattern of trade, under the assumption of symmetry, fluctuates stochastically, involves two-way endogenous international technology transfer and product cycles (when* $\sigma \neq ½$*), as well as intranational endogenous technology transfer. The extent of both technology transfer and product cycles is determined by the intensities of global innovative and imitative activities and relative national labor endowments.*

## 3.5 Conclusion

This paper constructs a Neo-Schumpeterian model of growth and trade between advanced countries. The model emphasizes the roles of costly and risky innovation and imitation, and incorporates instantaneous diminishing returns to each R&D activity. There is industrial targeting for R&D in which industries undergo cycles of innovation followed by imitation. Spillovers from innovation to imitation occur because unit costs of imitation are lower than those for innovation. Spillovers from imitation to innovation occur because R&D experience gained from imitative R&D activity lowers the costs of subsequent innovation. In this model, the integrated equilibrium can be achieved by free trade, with no DFI and no trade in R&D services.

The results of this model can be compared to previous work. In contrast to Grossman and Helpman (1991a), trade occurs under FPE, and innovation and imitation can occur in both countries. This allows the possibility of richer patterns of trade. These patterns of trade are similar to those in Dinopoulos et al. (1993), but there is no costless transfer of technology, a characterization consistent with the Industrial Organization literature on diffusion. In particular, the present model allows for technology transfer in both directions and for countries to capture part of the market in some industries, instead of the entire market.

# CHAPTER 4
# INTERNATIONAL R&D KNOWLEDGE SPILLOVERS

## 4.1 Introduction

> *[A]cademic and policy discussions...might be more fruitful if we spent less time working out solutions to systems of equations and more time defining precisely what the words we use mean.*
>
> *Romer (1993)*

Neo-Schumpeterian growth literature may not hinge on the existence of sizeable R&D knowledge spillovers, but they make the theorist's life easier. Consequently, empirical investigation into the nature, magnitude, and extent of spillovers of knowledge from R&D activity currently attracts a lot of attention. Detection of R&D spillovers is also important for accurate measurement of the social returns to R&D--critical for optimal R&D policy discussions. Nowhere, however, is the possible presence of spillovers more interesting than in the interactions among countries. It matters for foreign investment policy, national industrial policy, and international intellectual property rights protection. The new growth theory further suggests that strategies that increase the flow of spillovers will accelerate growth. Thus, it presents the enticing

possibilities of rapid economic development for some less developed countries and increased efficiency for fully integrated economies.

Unfortunately, these spillovers are extraordinarily difficult to identify and measure, despite numerous efforts to do so. Part of the problem is that theoreticians generally use exogenous spillover effects as a tool in their models rather than focus on theoretical examination of the forces that influence or are influenced by these spillovers. Additionally, because of the host of observability and definitional problems surrounding the concept of international R&D knowledge spillovers, empirical work is problematic. The theoretical and empirical importance of these spillovers was touched on in section 1.4 of Chapter 1. The current chapter is meant to address the question: what are spillovers and how do we measure them? The focus is on international, intraindustry R&D knowledge spillovers.

The main thrust of this chapter is to dispel the prevalent notion that spillovers are an unlooked for and costless boon to recipients; that, once acquired by one agent, the marginal cost of knowledge to other agents is close to zero. Just sitting in the physics section of the library does not make one a physicist. The prospective scientist must invest time and money.[1] Just so, firms must invest in R&D activities to copy the innovations of other firms in the industry. They may spend less because of information acquired as a result of the previous success, but if they do not engage in R&D activity, they will not enjoy any pure spillover benefits. Alternatively, firms may maintain small

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[1]Notwithstanding the possibility that playing tapes while you sleep or sleeping on a book may have some positive but costless effect.

investments in various auxiliary R&D programs that are designed to position the firm so as to maximize any expected spillover benefits from possible innovations by rivals or related industries. Studies that do not recognize these expenditures may present biased estimates of the magnitude of spillovers.

This chapter builds on the model of the previous chapter in order to clarify the issues involved in defining and measuring R&D knowledge spillovers. It is relatively straightforward to define a national quality index or stock of knowledge for the model presented in Chapter 3. An equation of knowledge accumulation can be derived and compared with estimated equations, in the existing literature, which attempt to measure international spillovers. I conclude from this comparison that the existing studies are not capturing true spillover effects because they do not distinguish between innovative and imitative R&D activity or account for other diffusion expenditures. Furthermore, 'spillover-seeking' behavior by profit maximizing firms militates against the presence of sizeable free-rider benefits from spillovers.

Section 4.2 discusses the meaning of R&D knowledge spillovers in detail. Section 4.3 extends the model of Chapter 3 to an operational equation of national knowledge accumulation which is compared to existing studies. Section 4.4 discusses issues of spillover measurement. Section 4.5 concludes.

## 4.2 What Are Spillovers?

Knowledge is nonrivalrous and at least partially nonexcludable, so it is no surprise that externalities, or spillovers, are associated with its production. What muddies the waters are the presence of more than one type of the flow commonly referred to as R&D spillovers, and, of course, the unobservable nature of knowledge. These various flows have different consequences for theory and policy so it is important to distinguish between them. I use Figure 4.1 to identify these flows and the associated spillover concepts.

Innovative R&D activity results in some new or improved process or product. Four benefit flows can be distinguished. The first stream includes all direct benefits that the innovator captures through (temporary) market power associated with the innovation. These flows may include profits from sales of superior products, productivity gains, and licensing. This stream, resulting from market transactions, is perhaps the easiest to measure. It represents the private return to R&D. When added to the three remaining flows, the result is the social return to R&D.

The second stream is direct benefits to customers of new products or existing products for which prices have dropped due to process innovations and competition. Because monopoly power is imperfect, and because the innovator may not foresee all of the uses of the new product, customers will not , in general, pay the full value of the innovation. This second flow is a pecuniary externality associated with the product. It

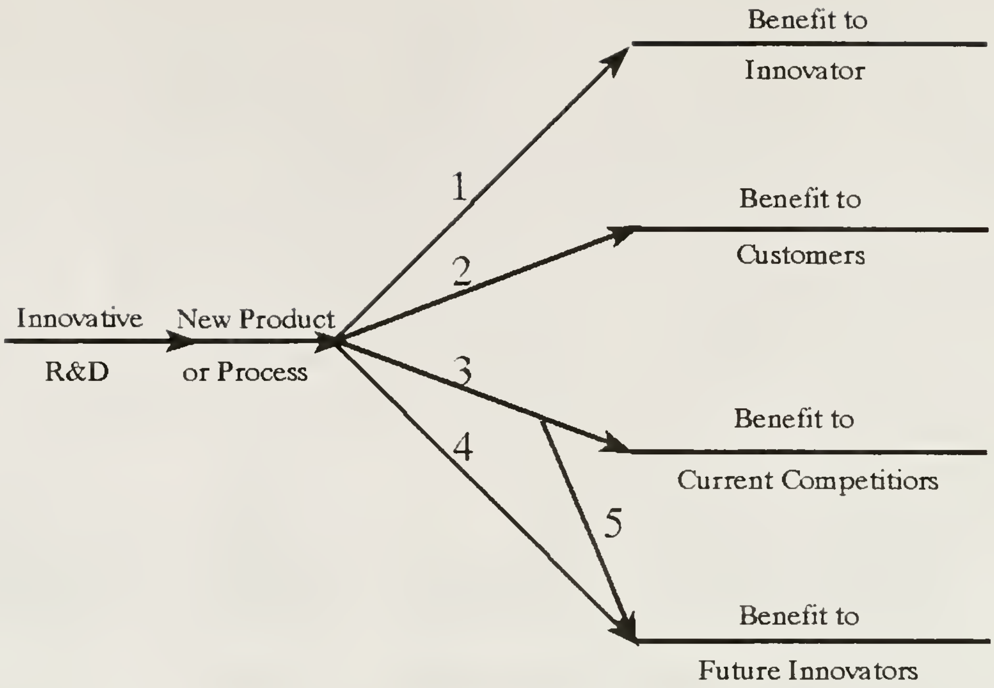


Figure 4.1
Benefit Flows From Innovation

arises because of market imperfections, competition, and measurement errors, not market failure. Accurate measurement of this potentially large benefit stream is essential for the calculation of the social return to R&D. Identifiable in principle, this flow is harder to measure than the first benefit stream. It does not represent, however, true R&D knowledge spillovers, although often measured as such.

Griliches distinguishes between the spurious spillovers of flow 2 in Figure 4.1 and what he calls true spillovers: "ideas borrowed by research teams of industry i from the research results of industry j." (1992, p. S36) Of course, i can equal j, and 'industry' can be replaced by 'firm.' Because I distinguish between innovative R&D activity and

imitative R&D activity, I further categorize these 'true' spillovers into two types according to the type of R&D activity of the recipient:[2]

The third flow is knowledge transfers to current competitors, who cannot be prevented from duplicating the new product or process at lower R&D cost. To the extent that competitors must devote resources to this noncooperative technology transfer, this is a measurable flow which is an externality to the innovator, not to the recipient. But, to the extent that the costs of imitating are lower than the costs of innovating because of the nonexcludable nature of knowledge, these are free-rider spillovers from (primarily) innovative activity to (primarily) imitative activity.[3] These are static spillover effects in the sense that they do more to affect current market structure than future knowledge accumulation. If innovation and imitation costs vary independently with the level of activity, the magnitude of these spillovers is endogenous.

The last benefit flow identified in Figure 4.1, flow 4, is the benefit to future innovators. This is the spillovers concept most often employed in the new growth models to overcome any long-run diminishing returns to R&D. It is also the most difficult flow to identify and measure, since it is related to the intertemporal, public-good

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[2]The stylized model of Chapters 2 and 3 envisions major innovations followed by exact duplication by imitators. In reality, imitators may make minor improvements to differentiate their products or improve a process while adapting and adopting it. These relatively minor changes could be interpreted as innovations in another model and may sum to substantial increments in knowledge. Individually, however, these 'imitations' will not have the same impact on knowledge production as major innovations.

[3]These spillovers are not just from reverse engineering or weak patent laws. The reduction in uncertainty, arising from the simple knowledge that a particular line of research was fruitful to a competitor, may be important, allowing the imitator to conduct a narrower research program.

nature of knowledge. These spillovers arise because those firms engaged in current R&D activities add to the stock of knowledge. This is a key factor in affecting future innovation in that industry and others. But, the ways in which these spillovers actually occur are difficult to quantify. They are of a different, more elusive, quality than the nonexcludability spillovers of flow 3 in Figure 4.1. It is not simply a matter of it being easier to copy than to create. It is picking up clues as to the nature of the unknown, which illuminate the most effective path to the next stage, competitive arena or state-of-the-art in the industry.[4] How can this effect be detected, especially if internalized by firms currently at the state-of-the-art, either through innovation or imitation, and engaged in a race to discover the next state-of-the-art in the industry?

There is both theoretical and empirical evidence that intraindustry transfers of this type require recipient R&D expenditures to be able to take advantage of any new additions to the knowledge stock.[5] Simultaneously engaging in similar innovative activity may position the firm to take advantage of spillovers from a rival, but concurrent maintenance R&D activity or subsequent imitative activity, or both, are substitutes for innovative activity in this role (flow 5 in Figure 4.1). Further, if the innovation is major, unsuccessful rivals may still require expenditures to copy the successor to maintain their R&D competitiveness and market share. Familiarity with the

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[4]Kortum (1995) suggests a search model of innovation in which successful research spills over to subsequent research by shifting the underlying distribution of undiscovered techniques, thus maintaining the pool of potential improvements.

[5] See Cohen and Leventhal (1989), Henderson and Cockburn (1995), Nadiri (1993), and Griliches (1992) on this point.

current state-of-the-art seems essential. So, in principle, these spillovers are also associated with R&D activity on the receiving end and are therefore endogenous.

## 4.3 Acquired Knowledge or Spillovers?

In this section I use the model previously developed in Chapters 2 and 3 to interpret current efforts to measure spillovers. Recall that, in this model, endogenous innovative and imitative R&D contribute to long-run growth in consumer utility through quality improvements. Both are Poisson processes with endogenous arrival rates. $I \equiv I(L_I)$, ($C \equiv C(L_C)$) is the arrival rate or intensity of innovative (or imitative) activity per industry, $L_I$ ($L_C$) is labor employed in innovative (or imitative) activity per industry, and $I'(L_I)>0$, $C'(L_C)>0$, $I''(L_I)<0$, $C''(L_C)<0$. There is free entry into each activity, firms are atomistic, and industries are targeted first for innovation and then for imitation. Below I reproduce the key equations of the integrated equilibrium:

$$v_I \equiv \frac{\pi_L + C v_C}{\rho + C} = u_I \tag{4.1}$$

$$v_C \equiv \frac{\pi_C}{(\rho + I)} = u_C \tag{4.2}$$

Equations 4.1 and 4.2 are the zero-profit conditions (ZPC) for innovative and imitative activity, respectively, in the steady state, where $\pi_L$ are dominant firm profits. $\pi_C$ are collusive profits, $\rho$ is the discount rate, and $u_I$ (or $u_C$) is the unit cost of innovative (or imitative) activity. Equations 4.1 and 4.2, along with a labor constraint (not reproduced here), completely describe the integrated equilibrium steady state.

In this model, with free trade between two advanced countries (Home and Foreign) and international capital mobility, growth in consumer utility is always equal in the two countries. A quality index can be defined, however, for which the global growth rate is equal to growth in consumer utility. A distinction can be made between this growth rate and the growth rates of national quality indices. Define the global quality index or stock of knowledge as

$$\Lambda_{Gt} = \int_0^1 \ln \lambda^{h_t(\omega)} d\omega \quad , \tag{4.3}$$

where $h_t(\omega)$ is the state-of-the-art quality in industry $\omega$ at time t, $\omega \in [0,1]$, and $\ln \lambda$ is the knowledge increment associated with each state-of-the-art product. Then, Appendix G shows that

$$\dot{\Lambda}_G = \beta^* I^* \ln \lambda \equiv g^* \quad , \tag{4.4}$$

where $g^*$, given in (3.19), is the steady-state rate of growth of global consumer utility, $I^*$ is the steady-state level of innovative activity or the mean rate of occurrence of innovations, and $\beta^*$ is the steady-state percentage of industries targeted for innovation, given in (3.11). The rate at which the world quality index grows equals the proportion of industries targeted for innovations, times the mean rate of occurrence of innovations, times the knowledge increment of each innovation. This growth rate is always equal to $g^*$.

Compare this with the growth rate of Home's stock of knowledge. Home's stock of knowledge is

$$\Lambda_{Ht} = \int_0^1 \ln \lambda^{h_{Ht}(\omega)} d\omega \quad , \tag{4.5}$$

where $h_{Ht}(\omega)$ represents the highest quality available in Home from domestic firms in industry $\omega$ at time t. In the steady state,

$$\dot{\Lambda}_H = (\alpha_F^* C_H^* + \beta^* I_H^*)\ln\lambda \quad . \tag{4.6}$$

where $\alpha_F^*$ is the percentage of Foreign monopolies targeted for imitation by Home firms, $C_H^*$ is the level of Home imitative activity per industry, and $I_H^*$ is the level of Home innovative activity per industry in the steady state. Home increases its stock of knowledge from both innovation and technology transfer from abroad through imitation. The term

$$\alpha_F^* C_H^* \tag{4.7}$$

represents the rate of technology transfer from abroad through imitation.

The national growth rates of knowledge can be compared to the global rate under the symmetric case already examined in Chapter 3. Recall that $\sigma$ is Home's share of the world labor endowment, and s is its share of final goods production. In the symmetric case, $\sigma$=s, $\alpha_F = (1-\sigma)\alpha^*$, $C_H = \sigma C^*$, and $I_H^* = \sigma I^*$, so that

$$\dot{\Lambda}_H = (\alpha_F^* C_H^* + \beta^* I_H^*)\ln\lambda = (2-\sigma)\sigma g^* > \sigma g^* \quad , \tag{4.8}$$

for $\sigma$ greater than zero. Home's stock of knowledge, and consumer utility, grow faster than its share of innovation would imply due to the costly international transfer of technology through imitation. So, even among advanced countries, international technology transfer is an important element of growth.

Equation (4.6) can be compared with a class of papers attempting to measure international spillovers of knowledge by estimating an equation of the general form

$$G = \delta_H R_H + \delta_F R_F + \epsilon_1 \ , \tag{4.9}$$

where G is growth in total factor productivity (TFP) or labor productivity, $R_H$ is some measure of Home R&D activity such as expenditures, $R_F$ is a measure of similar foreign R&D activity and $\epsilon_1$ is an error term. The parameter $\delta_F$ is thought to measure spillovers from foreign or borrowed R&D.[6] This equation is meant to measure the relative importance of Home and Foreign R&D for national productivity growth. Rewrite (4.6) as

$$\dot{\Lambda}_H = \tilde{\lambda}_C C_H^F + \tilde{\lambda}_I I_H + \epsilon_2 , \tag{4.10}$$

where $\tilde{\lambda}_C = \ln \lambda_C$, $\tilde{\lambda}_I = \ln \lambda_I$ and $\epsilon_2$ is an error term.[7] The impact on knowledge from the two sources is allowed to vary. An equation such as this can be estimated for the U.S. across industries and over time (time and industry subscripts omitted).

$\dot{\Lambda}_H$ is the gross increment in knowledge per period. This variable is not directly measurable, but a reasonable proxy could be the change in industry stock market value per period. If the degree of appropriability of the firm vis-a-vis the consumer is relatively constant, this method might sufficiently capture the net increases in the value or quality of the industry's products. Let $\dot{\Lambda}_H = \zeta \dot{S} + \epsilon_3$ , where $\dot{S}$ is the change in stock market value in each period. If $\zeta$ is constant across time and the variance of $\epsilon_3$ is

[6]See Nadiri (1993) and Griliches (1992), for discussions of this literature.

[7]In principle, other technology expenditure flows, such as patent purchases and licensing should also be considered. See Nadiri (1993) for evidence that these flows have increased. See Kokko (1994) and Saggi (1994) for discussions of spillovers associated with DFI.

small, this will be a reasonably good measure of the growth in quality or knowledge attributable to innovation.[8]

There are advantages to this approach. First, directly estimating the effects of R&D activity on firm value, not its impact on productivity, leaves aside the problem of separating out the effects of learning-by-doing and human capital accumulation, which do not have the observability of R&D, nor the news event characteristic of innovation. Second, this approach is not limited to process innovations, for which only a nonconstant portion of R&D is undertaken.[9] Third, it reduces the possibility of inadvertently capturing 'spurious' spillovers through incorrectly measured input prices (type 2 flows in Figure 4.1); the problem of correctly deflating R&D expenditures to obtain measures of real R&D activity is still present. Fourth, it reduces the timing problem of when R&D affects productivity. R&D news will be immediately incorporated into stock market values. Many studies use cumulative R&D flows to alleviate this difficulty,

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[8] An alternative is to use some quality adjusted patent count. See Griliches (1992) for a discussion of the shortcomings of patent data. Patents are said to be a noisy measure of innovative output. Some innovations aren't patented. Not all patents have value, and their value varies over time. Current received wisdom is that regressions of firm value on measures of R&D input perform better than such regressions with patent counts as the dependent variable. See Thompson (1995b). There have been recent attempts to improve our understanding of the relationship between innovation and patents. See Eaton and Kortum (1994) for a model of technical change and diffusion across countries in which the decision to patent is endogenized.

[9] Thompson (1995b) develops a model in which an innovation directly affects firm value, thus capturing the effects of both process and product innovations. The reduced form of his model also includes current profits as a determinant of firm value. Alternatively, a model of process innovation equivalent to the model developed in Chapters 2 and 3 could be used. In this case, $\dot{\Lambda}_H$ is equivalent to TFP growth.

which is especially problematic because the effects of foreign R&D may have longer lags than own R&D effects.

In equation 4.6, $C_H$ is per industry imitation activity, and $\alpha_F$ is the percentage of foreign monopolies targeted for imitation. Similarly, $I_H$ is the per industry innovative activity, and $\beta$ is the percentage of firms targeted for innovation. In practice, the intensity of R&D activity and its impact on the stock of knowledge will vary across industries, and innovative and imitative activity will occur simultaneously in each industry.[10] So, in (4.10), $\alpha_F^* = \beta^* = 1$ and $\bar{\lambda}_C$ measures the average impact on the national knowledge stock of primarily imitative activity directed at noncooperative technology transfer from abroad in each industry. The impact of Home innovative activity is $\bar{\lambda}_I$.[11]

Note that, in (4.9), $R_H = C_H^F + C_H^H + I_H$. The difference between $\bar{\lambda}_I$ and $\delta_H$ is that $\delta_H$ measures the impact of all Home R&D activity, forcing $\bar{\lambda}_I = \bar{\lambda}_C$, and overmeasuring, by $C_H^H$, the R&D activity directed at increasing the national knowledge stock. By similar reasoning, $\delta_F$ measures the effect of foreign R&D, $R_F = C_F + I_F$, without recognizing that $C_F$ should have little effect and without considering the costs of bringing about these 'spillovers' (namely $C_H^F$). In contrast, $R_F$ does not enter into (4.10).

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[10]See Klenow (1994) for a model that explains cross industry variations in R&D activity through variations in technological opportunity, market size, and appropriability of innovations. See Davidson and Segerstrom (1994) for a model qualitatively similar to that of Chapter 3 but in which innovation and imitation occur simultaneously in each industry.

[11]A term could also be added that measures aggregate national imitative activity to test the assumption, made in Chapter 3, that imitative activity may directly contribute to the stock of knowledge, through learning-by-doing in R&D.

Much of what is considered spillovers may be costly transfers, which can be estimated through diffusion expenditures. $\delta_H$ may underestimate the effectiveness of $I_H$, and $\delta_F$ may not be accurately capturing spillover effects.

To illustrate this last point, ignore the differences between the left-hand side (LHS) of equations (4.9) and (4.10), or assume $\dot{\Lambda}_H = G$, as in footnote 9. Suppose that Home innovation can be related to total Home R&D, and the intensity of imitation of Foreign innovations is positively related to the intensity of foreign innovation:

$$I_H = aR_H + e_1, \qquad a<1$$

and

$$C_H^F = bR_F + e_1.$$

Substituting these into (4.10), and comparing the result to (4.9) shows that, if (4.10) is the true model, then $\delta_H = a\bar{\lambda}_{IH} < \bar{\lambda}_{IH}$, $\delta_F = b\bar{\lambda}_C \neq \bar{\lambda}_C$, and $\epsilon_1 = \epsilon_2 + \bar{\lambda}_I e_1 + \bar{\lambda}_C e_2$. Note that the effectiveness of Home innovative R&D, , $\bar{\lambda}_{IH}$ is underestimated by $\delta_H$ , and $\delta_F$ is inaccurately capturing the effectiveness of Home imitative R&D, which may include spillovers from Foreign R&D. Furthermore, Variance($\epsilon_1$) > Variance($\epsilon_2$). These facts imply that equation (4.10) should improve over (4.9).

The question is, then, how to allocate expenditures between substantially innovative activity and substantially imitative activity. If this cannot be done efficiently and satisfactorily, then estimating equation (4.11) will not improve over (4.10). One possibility is to allocate by size of research programs. It could be assumed that small programs are, primarily, maintained in order to facilitate spillovers, while large programs

are innovative.[12] This separates R&D activity into imitative and innovative activity, but the proportion of imitative activity directed at foreign firms must be determined. If there are adequate data on patent infringement complaints, then the ratio of foreign complaints against domestic firms to total complaints against domestic firms, $\xi$, can provide an estimate of $C_H^F$.[13] Then,

$$\hat{C}_H^F = \xi C_H + \epsilon_4 \ . \tag{4.11}$$

Finally, $C_H$ and $I_H$ must be converted from unobserved intensities of R&D activity into R&D expenditures. Suppose that, instead of the specific functional forms of Chapters 2 and 3, $C_H$ and $I_H$ take the following forms:

$$C_H = a_C L_{CH}^{\theta} \tag{4.12}$$

and

$$I_H = a_I L_{IH}^{\phi} \ . \tag{4.13}$$

Since the primary purpose is not to measure diminishing returns to R&D, assume that $\theta = \phi$, for which estimates are provided for 16 industry groups by Thompson (1995b). Substituting for these in (4.12) and (4.13), and using (4.11), allows (4.10) to be rewritten as

$$\dot{S} = \gamma_1 L_{CH}^{\hat{\theta}} + \gamma_2 L_{IH}^{\hat{\phi}} + \epsilon_5 \ , \tag{4.14}$$

where

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[12]This could be expensive and time-consuming, of course, requiring a high degree of disaggregation, but this regression could be done for a single industry. Henderson and Cockburn (1995), for example, have collected such data for the pharmaceutical industry.

[13]Alternatively, since imitators must often license some key component, licensing data may be useful.

$$\gamma_1 = \frac{\bar{\lambda}_C \xi a_C}{\zeta}$$

$$\gamma_2 = \frac{\bar{\lambda}_I a_I}{\zeta} , \tag{4.15}$$

and

$$\epsilon_5 = \frac{\epsilon_2 - \epsilon_3 + \bar{\lambda}\epsilon_4}{\zeta}$$

$L_{CH}$ and $L_{IH}$ can be interpreted as innovative and imitative R&D expenditures, respectively. These are allocated, as discussed above, by research program size, and may be measured with error, but $E(\epsilon_5)$ is still zero. The variable $\xi$ is constructed from patent infringement data, licensing data, or other data that might be used to distinguish between imitative activities directed at Home and Foreign firms.

From examination of (4.14) and (4.15), distinguishing between these R&D flows is important. Notice that even if $\lambda_C = \lambda_I$, $\theta = \phi$, and $a_I = a_C$, then $\gamma_1 \neq \gamma_2$, because only a fraction of imitative activity is directed at foreign firms. $\gamma_1$ and $\gamma_2$ measure the impact on the quality or knowledge index of imitative activity that transfers technology from abroad and innovative activity that creates knowledge at home. If $\lambda_C = \lambda_I$, as implied by the model, and $\theta = \phi$, then $\gamma_1 / \xi > \gamma_2$ implies that $a_C > a_I$. In what sense, then, can this be called a measure of the magnitude of spillovers from innovators to imitators? This is the topic of the next section.

## 4.4 Measuring Spillovers

For the model used here, type 4 spillovers in Figure 4.1 are exogenous. Type 3 spillovers, however, those from innovators to imitators are endogenous, at least in the sense to be explained below. If $a_C$ in (4.12) is greater than $a_I$ in (4.13), and $\theta = \phi$, the same level of effort gives a higher probability of successful imitation than innovation. If the only factor of R&D production is labor, which is the numéraire, (4.12) and (4.13) imply unit costs of

$$u_C = \left(\frac{1}{a_C}\right)^{1/\theta} C^{\frac{1-\theta}{\theta}} \equiv \bar{a}_C C^{\bar{\theta}} \tag{4.16}$$

and

$$u_I = \left(\frac{1}{a_I}\right)^{1/\phi} I^{\frac{1-\phi}{\phi}} \equiv \bar{a}_I I^{\bar{\phi}} \tag{4.17}$$

Let

$$S_{MI} \equiv \frac{\bar{a}_C}{\bar{a}_I} \tag{4.18}$$

and

$$S_{MF} \equiv \frac{u_C^*}{u_I^*} \tag{4.19}$$

be defined as the magnitude of intraindustry spillovers from innovators to current competitors at the industry and firm levels respectively. Equation 4.18 is exogenous, presumably determined by such effects as industry specific appropriability characteristics and information technology. In (4.19), unit costs are determined in equilibrium (as indicated by *) at the industry level, by, among other things, $\bar{L}$, the world labor

endowment. $S_{MF}$ could also be affected by intellectual property rights protection, subsidies and firms' expectations about future profits.

If firms are atomistic, then they take (4.19) as given. If $S_{MF} < 1$, then there are exogenous spillovers at the firm level as well. But,

$$S_{MF} \equiv \frac{u_C^*}{u_I^*} = \frac{v_C^*}{v_I^*} \tag{4.20}$$

and $v_C^* < v_I^*$, by construction, in this model. Since the successful imitator splits the market with the innovator, the expected discounted benefits to imitation cannot exceed the expected discounted benefits to innovation. Of course, this need not be generally true.

In any case, $S_{MI} \neq S_{MF}$ except by coincidence (or if unit costs are constant, which is not borne out by the substantial empirical evidence of instantaneous diminishing returns to R&D)[14]. So, if the regression described in section 4.3 is carried out and an estimate of $S_{MI}$ is obtained, it must be interpreted as occurring at the industry level. Firm level type 3 R&D spillovers from innovative activity to imitative activity, $S_{MF}$, may be larger or smaller than those which occur at the industry level.[15] Which measure of spillovers to use matters depends on the context. $S_{MI}$ is independent of policy; $S_{MF}$ is not.

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[14]See Griliches (1992), Nadiri (1993), Thompson (1995b), and Henderson and Cockburn (1995) for evidence of instantaneous diminishing returns to R&D.

[15]This discussion assumes, as in Chapter 2 and 3, that $u_I^*$ and $u_C^*$ are determined independently and at the industry level. How realistic this assumption is depends on industry specific characteristics. It may take specific skills to run smaller programs designed to duplicate another's success as cheaply as possible, as compared to running large innovative projects. If these specific skills are in fixed supply and firms are small and competitive, then these costs will be independent.

The magnitude of spillovers from innovators to imitators is important for the discussion of North-South trade. There are many models that imply that imitation coupled with production cost advantages is an effective course of economic development.[16] The larger the magnitude of spillovers, the more effective this course of development. A key issue is the possible existence of a geographic dimension to spillovers. In (4.18), $\bar{a}_C$ may be a function of distance from the innovating firm or country because, say, spillovers work partially through the labor markets. This is a natural barrier to foreign competition, which may be counteracted by the foreign government through policies which affect $S_{MF}$. These may include designing intellectual property rights protection laws that favor imitators or subsidizing imitation.

This type of spillover also matters for national patent law and optimal R&D policy. In welfare considerations, the benefits of imitation are usually considered to be lower prices and increased variety. These are balanced against the incentives to innovate. A complicating factor is the existence of the innovation to innovation spillovers of type 5 in Figure 4.1. To the extent that imitators can expect spillovers to their own innovative activity and incorporate these expectations in $v_C$, they will increase their imitative activity. This imitation may be the most efficient means of staying competitive in R&D, and this consideration must also be balanced against the incentives to current innovators.

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[16]See, for example, Grossman and Helpman (1991a) and Barro and Sala-I-Martin (1995), Ch 8.

Although this chapter does not model spillovers from innovation to innovation of type 4 in Figure 4.1, it does offer some observations. A dominant theme of the chapter has been the necessity of engaging R&D activity in order to benefit from spillovers. Just as imitators may incorporate anticipated spillovers into expected benefits, $v_C$, innovators will incorporate them into $v_I$. Cohen and Levinthal build a model in which "absorptive capacity represents an important part of a firm's ability to create new knowledge," and in which "spillovers may encourage [innovative] R&D under some conditions." (1989, pp. 570, 574)

This 'spillover-seeking' behavior by innovators complicates the discussion of optimal R&D policy further. Increasing the ease of dissemination of knowledge may <u>increase</u> innovation. Moreover, these increased expenditures may lower the magnitude or value of anticipated spillovers. For type 3 spillovers, in Figure 4.1, if $v_C$ is large relative to $v_I$, firm level spillovers will be small, even if industry level spillovers are large. If the magnitude of type 4 spillovers per innovation does not increase with the level of innovative activity ( $v_I$ does not increase with I) , the same effect can occur there.

Evidence that firms engage in efforts to capture spillovers abounds. Nadiri (1993) reports that a significant proportion of R&D conducted in the U.S. is done by foreign firms--possibly attempting to counteract any geographic spillover disadvantages. Nadiri also reports an increase in recent years of joint ventures in R&D. One motive for these ventures is to internalize potential spillovers. Henderson and Cockburn (1995) provide

evidence that economies of scope in the pharmaceutical industry may be generated by intrafirm spillovers.

The implication of this behavior is that there may not be as much of a role for strategic industry policy based on spillovers as popularly conceived. Firms will inevitably have superior information about the magnitude and direction of potential spillovers than the government (or economists) and will incorporate this information into their decisions. The market imperfections associated with knowledge production and dissemination may not be as large as commonly believed, at least in well developed markets.[17]

## 4.5 Conclusion

This chapter is concerned with the meaning and measurement of international intraindustry R&D knowledge spillovers. Because there seems to be some confusion in the literature as to the precise nature of R&D knowledge spillovers, I spend some time discussing the concept. I develop an equation of knowledge accumulation through innovation and costly technology transfers from abroad. This is compared to existing efforts to detect international spillovers of knowledge. I conclude that many existing

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[17]Thompson (1995a) looks at the consequences of industrial espionage and piracy for international relations. He cites the example of Chinese firms illegally producing bootleg compact disks and computer software, infringing on U.S. firms' copyrights. He points out that the gravity of the situation is due to the implicit involvement of the Chinese government in a 'policy of piracy.'

measures of spillovers are biased and that spillover-seeking behavior by firms engaged in R&D lowers the magnitude of *ex ante* spillovers.

Future work includes testing the knowledge accumulation equation developed in the paper to see if it improves over existing studies in measuring the relative importance of technology transfers from abroad. It also remains to endogenize innovation to innovation spillovers, both intra and interindustry, and attempt to ascertain their avenues of transmission and magnitudes. Finally, it may be useful to develop a model in which these spillover magnitudes are possibly affected by the avenue of international transmission.

# CHAPTER 5
# WHAT'S NEXT?

Research sometimes poses more questions than it answers: mine is no exception. Chapter 1 briefly addressed the question of whether there are long-run diminishing returns to R&D. Of course, a lifetime of research may not answer this question, but it is still worth asking. Sustained long-run growth is an important goal of many peoples. This dissertation represents an increment of knowledge, however small, in understanding this process and may even generate spillovers to future work. My efforts center on the distinction between R&D activities focussed on bringing about major breakthroughs (innovative) and those directed at duplicating existing products or processes (imitative).

This distinction, when introduced by Segerstrom (1991) into the quality ladders model of Grossman and Helpman (1991b), provided an interesting opportunity to explore the art of modeling. In Chapter 2, I showed that sufficient instantaneous diminishing returns to each R&D activity (innovative and imitative) are necessary for stability and 'normal' comparative statics in Segerstrom's model. There is considerable empirical support for the existence of diminishing returns to R&D, but it is not clear whether innovative and imitative costs are determined separately, as implied by the model. If innovation and imitation require separate skills, their relative intensities could be affected by differential subsidy.

More possibilities for new research are uncovered in Chapter 3. The international transfer of technology and its influence on trade patterns among advanced countries are the subject of that chapter. Considerable generalization of the model is possible. The R&D technology used is rather limiting because it implies that unit costs are determined at the global level. If different technologies are used, allowing R&D unit costs to be determined at the national level, trade patterns can be analyzed when FPE doesn't hold. Can a range of relative endowments be determined for which the collusive equilibrium can be sustained, even with small wage differentials?

Another useful endeavor is to introduce alternative avenues (to imitation) of international technology transfer and explore the effects of policy on the relative importance of these different avenues. Costly DFI can be introduced, as can the possibility of licensing. In a model of process innovation, for example, is the magnitude of potential spillovers maximized through encouraging DFI, imitation, or some combination? Does the answer depend upon the degree of similarity between the relevant countries' technology bases?

This last question leads to yet another implication of the model of Chapter 3. The assumption of an exogenous learning-by-doing effect, by which imitative R&D plays a vital role--not just in diffusing current technology, but in refining the research techniques vital for future innovation--begs for formal modeling. There are dual aspects to this learning. First, for the successful firm (or country), and, to a lesser extent, all engaged in the imitation race, achieving the end product--knowledge--allows the firm (or country) to travel closer to the technology frontier. This would seem to be a necessity if the firm

(or country) wanted to compete in this market through innovation. To know what the next step up the ladder might be, it is necessary to be familiar with the current state-of-the-art. Second, all firms engaged in an imitation race gain experience in conducting R&D. The refinement of R&D technique brings with it a better knowledge of what is possible. I would combine both of these aspects into a simple realization of declining costs of further innovation.

This setup could be the basis of a development model. It is possible to conceive of an evolution in the pattern of technology transfer between the North and the South as the latter proceeds along the development path. Initially, DFI is predominant, giving rise to the traditional product cycle. Over time, the receiving country collects experience (even in this cooperative transfer, the transferee must <u>learn</u> the technology and will inevitably sharpen her learning skills). Once some critical mass of experience (human capital, knowledge) is reached, noncooperative imitation commences. The country can now <u>choose</u> to target the latest products and techniques, thus bringing itself closer to the technological frontier and accelerating its learning in R&D. Again, once some critical mass is reached, innovation can begin.

However, the story and the transition is not so simple. Some level of human capital (education) seems necessary. More importantly, the process of innovation requires an available pool of basic knowledge (scientific inventions or discoveries). Not just in a few industries but across the whole range of human knowledge. This is because of the heavy reliance on outside knowledge by innovators. It is hard to imagine how radiation therapy could have been developed in a country that did not understand nuclear

physics. How accessible this base of knowledge is for the individual country depends on the geographic nature of knowledge spillovers and the prevailing intellectual property rights (IPP).

So, a broad based R&D sector, actively fueled by ongoing basic research, must be maintained, at least at the global level, and, to a varying extent, at the national level, depending on the nature of spillovers, the brain drain, IPP, etc. Of course, the critical mass necessary will vary by industry so that some industries may emerge as world class competitors before others. In this context, we can look at IPP, trade and industrial policy in each phase. Should patent protection be the same in the North and the South? Or should patent protection evolve with economic development? Most North-South growth models that examine IPP (see Taylor [1993a,b], [1994]) look at the trade-off between Southern and Northern interests, which are invariably opposed. What if the North benefits from Southern imitation? What if continued innovation becomes difficult without the broad diffusion through imitative R&D that results in learning in R&D and standardization of the product? This imitation by the South might actually allow the North to specialize in innovation.

An implicit component of the foregoing discussion is the possibility that spillovers of knowledge flow in all directions, not just from North to South. The focus of Chapter 4 is the measurement of knowledge spillovers, which is complicated by numerous theoretical and empirical difficulties. I show that studies that do not account for diffusion expenditures will present biased estimates of the relative contributions of national and foreign R&D to the national stock of knowledge. The next step in this line of research

is to empirically implement the equation of knowledge accumulation developed there. Positive results would provide insight into the correct methodology for measuring spillovers.

That equation, however, does not shed light on the presence and magnitude of spillovers from innovation to innovation. Of course, building a theoretical model which endogenously captures spillovers of both type 4 and type 5 in Figure 4.1 would be quite useful for formal analysis of the various policy questions involved in maximizing the social return to R&D. In Cohen and Levinthal (1989), firms explicitly account for the value of spillovers from the R&D activities of others, when choosing their level of investment in R&D. Caballero and Jaffe (1993) use patent citation data to track spillovers from innovation to innovation. Both models capture essential aspects of the process, but neither include endogenous diffusion or its possible contribution to knowledge, an avenue I intend to pursue.

## APPENDIX A
## CONSUMER PROBLEM

### A.1 Derivation of Equation 2.3

Let the consumer's lifetime budget constraint be given by

$$\int_0^\infty e^{-R(t)}E(t)\,dt = A(0) \quad . \tag{A.1}$$

where A(0) is initial assets plus the present value of future factor income, R(t) is the cumulative interest factor $\int_0^t r(s)\,ds$ , and the instantaneous budget constraint is

$$E(t) = \int_0^1 \left\{ \sum_{j=0}^\infty p_{jt}(\omega)\, d_{jt}(\omega) \right\} d\omega \quad . \tag{A.2}$$

The consumer problem is solved in two stages. To maximize (2.2) subject to (A.2), form the Hamiltonian

$$H = \ln\left[ \sum_{j=0}^\infty \lambda^j d_{jt}(\omega) \right] + \mu(\omega) \left[ \sum_{j=0}^\infty p_{jt}(\omega) d_{jt}(\omega) \right] \quad . \tag{A.3}$$

where (A.2) is the transversality condition and E(t) is the state variable for which

$$E'(\omega) = \left[ \sum_{j=0}^\infty p_{jt}(\omega) d_{jt}(\omega) \right] \quad . \tag{A.4}$$

The necessary conditions are

$$\frac{\partial H}{\partial d_{kt}} = \frac{\lambda^k}{\sum_{j=0}^{\infty} \lambda^j d_{jt}(\omega)} + \mu(\omega) p_{kt}(\omega) = 0 \qquad , \; k = 0, \ldots, \infty \tag{A.5}$$

and

$$\mu'(\omega) = 0 \quad \Rightarrow \quad \mu(\omega) = c \; . \tag{A.6}$$

Putting (A.6) into (A.5), rearranging and noting that k is arbitrary gives

$$\frac{p_{kt}(\omega)}{\lambda^k} = \frac{1}{c\left[\sum_{j=0}^{\infty} \lambda^j d_{jt}(\omega)\right]} \qquad k = 0, \ldots, \infty \; . \tag{A.7}$$

This implies that

$$\frac{p_{jt}(\omega)}{\lambda^j} = \frac{p_{kt}(\omega)}{\lambda^k} \Rightarrow \frac{p_{kt}(\omega)}{p_{jt}(\omega)} = \frac{\lambda^k}{\lambda^j} \qquad k\,,\, j = 0, \ldots, \infty \tag{A.8}$$

(The marginal rate of substitution or price ratio for any two goods in $\omega$ with positive demand is constant). Using (A.8) and rearranging (A.7) gives

$$\begin{aligned} \frac{1}{c} &= \frac{p_{kt}(\omega)}{\lambda^k} \sum_{j=0}^{\infty} \lambda^j d_{jt}(\omega) \\ &= \sum_{j=0}^{\infty} \frac{p_{jt}(\omega)}{\lambda^j} \lambda^j d_{jt}(\omega) \\ &= \sum p_{jt}(\omega) d_{jt}(\omega) \\ &= E(t) \end{aligned} \tag{A.9}$$

by (A.2) and the fact that the total measure of industries is set to 1. Then E(t) / 1 is the per industry expenditure. Combining (A.7) and (A.9),

$$\frac{E(t)\,\lambda^h}{p_{ht}(\omega)} = \lambda^h d_{ht}(\omega) \tag{A.10}$$

or

$$d_{jt}(\omega) = \begin{cases} E(t)/p_{jt}(\omega) & \text{for} \quad j = h_t(\omega) \\ 0 & \text{else} \end{cases}$$

as in equation 2.5.

## A.2 Derivation of Equation 2.4

Maximizing (2.1) subject to (A.1) at time t=0 gives the consumer's optimal expenditure path over time given all information at time t=0. Substituting from (2.2) and (2.3) into (2.1) gives

$$\begin{aligned} U &= \int_0^\infty e^{-\rho t} \int_0^1 \ln\left\{\frac{\lambda^h E(t)}{p_{ht}(\omega)}\right\} d\omega\, dt \\ &= \int_0^\infty e^{-\rho t} \left\{ \int_0^1 \ln \frac{d\omega}{p_{jt}(\omega)} + \ln E(t) + h \ln \lambda \right\} dt \ . \end{aligned} \tag{A.11}$$

For this problem, expenditure is the control variable and the level of assets is the state variable, for which

$$\dot{A}(t) = r(t)A(t) + I - E(t) \ . \tag{A.12}$$

Here, $r(t) = R'(t)$ and $I(t)$ is current factor income. The transversality condition is (A.1). The current value Hamiltonian is formed by adding the bracketed integrand of (A.11) to (A.12) multiplied by the shadow price of asset accumulation:

$$H = \ln E(t) + \lambda(t)[r(t)A(t) + I - E(t)] + \int_0^1 \ln \frac{d\omega}{p_{jt}(\omega)} d\omega + h \ln \lambda \ . \tag{A.13}$$

The necessary conditions are

$$\frac{1}{E(t)} - \lambda(t) = 0 \tag{A.14}$$

and

$$\dot{\lambda}(t) = \rho \lambda(t) - r(t)\lambda(t) \ . \tag{A.15}$$

Rearranging, (A.15) becomes

$$\frac{\dot{\lambda}(t)}{\lambda(t)} \quad p \quad r(t) \quad . \tag{A.16}$$

Differentiating (A.14),

$$\dot{\lambda}(t) \quad \frac{\dot{E}}{E^2}$$

and substituting this and (A14) into (A16) gives

$$\frac{\dot{E}(t)}{E(t)} \quad r(t) \quad \rho \quad .$$

which is equation (2.4) in the text.

# APPENDIX B
# DERIVATION OF COBB-DOUGLAS UNIT COSTS

Let

$$I = A_I L_I^{\epsilon} K_I^{1-\epsilon} \qquad 0<\epsilon<1 \tag{B.1}$$

$$C = A_C L_C^{\gamma} K_C^{1-\gamma} \qquad 0<\gamma<1 \ .$$

Then , since $w = 1$, by normalization, $w_I$ is the relative return to innovative capital (similarly for $w_C$) and

$$w_I = \frac{MPK_I}{MPL_I} = \frac{1-\epsilon}{\epsilon}\frac{L_I}{K_I} = \frac{1-\epsilon}{\epsilon}\frac{1}{A_I^{1/\epsilon}}\left(\frac{I}{K_I}\right)^{1/\epsilon} \tag{B.2}$$

$$w_C = \frac{1-\gamma}{\gamma}\frac{L_C}{K_C} = \frac{1-\gamma}{\gamma}\frac{1}{A_C^{1/\gamma}}\left(\frac{C}{K_C}\right)^{1/\gamma} ,$$

where (B.1) is used to substitute for $L_I$ and $L_C$. Also,

$$a_{LI} = \frac{1}{A_I}\left(\frac{L_I}{K_I}\right)^{1-\epsilon} = \frac{1}{A_I^{1/\epsilon}}\left(\frac{I}{K_I}\right)^{\frac{1-\epsilon}{\epsilon}} = \frac{1}{A_I}\left(\frac{\epsilon}{1-\epsilon}\right)^{1-\epsilon} w_I^{1-\epsilon} \tag{B.3}$$

$$a_{LC} = \frac{1}{A_C}\left(\frac{L_C}{K_C}\right)^{1-\gamma} = \frac{1}{A_C^{1/\gamma}}\left(\frac{C}{K_C}\right)^{\frac{1-\gamma}{\gamma}} = \frac{1}{A_C}\left(\frac{\gamma}{1-\gamma}\right)^{1-\gamma} w_C^{1-\gamma} ,$$

where (B.1) is used to substitute for $L_I$ and $L_C$ in the second equality and (B.2) is used in the third equality to substitute for $L_I/K_I$ and $L_C/K_C$. Next,

$$a_{KI} = \frac{1}{A_I}\left(\frac{K_I}{L_I}\right)^{\epsilon} = \frac{K_I}{I} = \frac{1}{A_I}\left(\frac{1-\epsilon}{\epsilon}\right)^{\epsilon}\frac{1}{w_I^{\epsilon}} \tag{B.4}$$

$$a_{KC} = \frac{1}{A_C}\left(\frac{K_C}{L_C}\right)^{\gamma} = \frac{K_C}{C} = \frac{1}{A_C}\left(\frac{1-\gamma}{\gamma}\right)^{\gamma}\frac{1}{w_C^{\gamma}} ,$$

using (B.1) and (B.2). Finally,

$$u_I = \frac{1}{\epsilon A_I}\left(\frac{L_I}{K_I}\right)^{1-\epsilon} = \frac{1}{\epsilon A_I^{1/\epsilon}}\left(\frac{I}{K_I}\right)^{\frac{1-\epsilon}{\epsilon}} = \frac{1}{\epsilon A_I}\left(\frac{\epsilon w_I}{1-\epsilon}\right)^{1-\epsilon} \tag{B.5}$$

$$u_C = \frac{1}{\gamma A_C}\left(\frac{L_C}{K_C}\right)^{1-\gamma} = \frac{1}{\gamma A_C^{1/\gamma}}\left(\frac{C}{K_C}\right)^{\frac{1-\gamma}{\gamma}} = \frac{1}{\gamma A_C}\left(\frac{\gamma w_C}{1-\gamma}\right)^{1-\gamma}$$

using (B.1), (B.2), (B.3), (2.5) and (2.6). Let $a_I = \left(\frac{1}{\epsilon A_I^{1/\epsilon}}\right) K_I^{\frac{\epsilon-1}{\epsilon}}$ and $\frac{1-\epsilon}{\epsilon} = \theta$.

Let $a_C = \left(\frac{1}{\gamma A_C^{1/\gamma}}\right) K_C^{\frac{\gamma-1}{\gamma}}$ and $\frac{1-\gamma}{\gamma} = \phi$. Then, the second equality in each line of (B.5) corresponds to (2.5) and (2.6) respectively. Note that

$a_{LI} = \frac{1}{A_I^{1/\epsilon}}\left(\frac{I}{K_I}\right)^{\frac{1-\epsilon}{\epsilon}} = \epsilon u_I = \epsilon a_I I^{\theta}$ and $a_{LC} = \frac{1}{A_C^{1/\gamma}}\left(\frac{C}{K_C}\right)^{\frac{1-\gamma}{\gamma}} = \gamma u_C = \gamma a_C C^{\phi}$.

# APPENDIX C
# PROOF OF STEADY-STATE CHARACTERISTICS

Below, I prove that only outside firms will conduct R&D. By Assumptions A1, A2, and A3, there is no imitative activity in $\beta$ industries. What remains to be shown is that current producers in $\alpha$ and $\beta$ industries won't innovate. The proof is different for the models of Chapters 2 and 3.

## C.1 Chapter 2

### C.1.1 Proof that Quality Leaders in $\alpha$ Industries Won't Engage in Innovative R&D

There are two types of industries, $\alpha$ (monopolies) and $\beta$ (duopolies). Let us assume that innovation occurs only in $\beta$ industries and see what happens when <u>one</u> incumbent monopolist in an $\alpha$ industry chooses to innovate. Denote the intensity of innovative activity by the monopolist as $I_D$. Since the monopolist, being only one firm in one industry in a continuum, is small, it can engage in innovative activity at $u^*_I$ unit costs (* denotes steady-state value).

If a single quality leader innovates (before imitation occurs) it can charge $p_D \quad \lambda^2$ and earn $\pi_D \quad (1 \quad 1/\lambda^2)E$. But, since $\pi_D/2 > \pi_C$, the competitive fringe of outside imitators will choose $C_D \rightarrow \infty$ at $u^*_C$ (since this is only one industry, imitation

can increase without bound and without affecting $u^*_C$) and the incumbent innovator will be instantly imitated. A third firm (after imitation occurs) will not find it profitable, relative to other industries, to continue to engage in imitative activity if $\lambda > 3$, which is true by Assumption A3. In that case,

$$(1 - 1/\lambda^2)\ E/3 < E/3 < (1 - 1/\lambda)\ E/2 = \pi_c\ .$$

Then the expected net benefit from further innovation by a current single quality leader is

$$v_D = \int_0^\infty \left( \int_0^\tau [-u_I^* I_D + \pi_L] e^{-\rho t} dt + v_x e^{-\rho\tau} \right) (I_D + C^*) e^{-(I_D + C^*)\tau} d\tau$$

where $\tau$ is the time until either imitation by the competitive fringe or innovation by the quality leader. $-u^*_I I_D$ is R&D expenditure by the quality leader at each time, t, and $\pi_L$ is earned until $\tau$ on sales of the current state-of-the-art quality. Expected profits after $\tau$ are

$$v_x = \frac{C^* v_C + I_D v_{CC}}{I_D + C^*}\ ,$$

where $v_C$ is given in (2.14) and $v_{CC} = \dfrac{\pi_D/2}{\rho + I^*}$ is the expected discounted collusive profits in this case. Thus,

$$v_D = \frac{-u_I^* I_D + (\rho + C^*) u_I^* + I_D v_{CC}}{(\rho + I_D + C^*)}\ , \tag{C.1}$$

where (2.15) is used to substitute for $\pi_L + C^* v_C^*$. To determine whether this firm has an incentive to innovate, differentiate $v_D$ w. r. t. $I_D$:

$$\frac{\partial v_D}{\partial I_D} = \frac{-2u_I^* + v_{CC}}{(\rho + I_D + C^*)^2}\ . \tag{C.2}$$

In order to rule out innovative activity by an $\alpha$ industry leader, it must be true that $\partial v_D/\partial I_D < 0$. This will be true if $v_{CC}$, the expected discounted profits to further innovation, is always less than $v^*_I = u^*_I$, the expected profits without further innovation

plus $u^*_I$, the unit cost of further innovation. Rewrite $v_{CC}$ and $v_I$ as (using equations 2.7, 2.8, 2.14, 2.15 and Assumption A3)

$$v_{CC} = \left(\frac{\lambda+1}{\lambda}\right)v_C < 2v_C \tag{C.3}$$

and

$$v_I = \frac{(2(\rho+I^*)+C^*)v_C}{\rho+C^*} = \frac{\rho+2I}{\rho+C^*}v_C + v_C \, . \tag{C.4}$$

It should be clear by comparison of (C.3) and (C.4), and noting that $u_C = v_C$, that $2u_I^* > v_{CC}$, $\partial v_D/\partial I_D < 0$ and that the incumbent firm has no incentive to innovate.

C.1.2 Proof that a Quality Leader in a $\beta$ Industry Will Not Innovate

A $\beta$ industry is already the subject of an innovation race by outside firms. So, for a $\beta$ industry leader to innovate it must be able to expect higher profits from doing so than the outside firms. Since it is price constrained, if it innovates, by the other quality leader, it can only expect to earn $\pi_L$, given in (2.7), until imitated. The other dominant firm can, if it imitates, earn profits of $\pi_D/2$. So it will devote $C_D \rightarrow \infty$ to imitation and the innovator will earn $v_{CC}$, defined earlier, until the next innovation occurs. Then, the expected net benefit is

$$v_D = \frac{\pi_C C - u_I^* I_D + I_D v_{CC}}{(\rho+I_D+I^*)} \tag{C.5}$$

and, using (2.14) and (C.3),

$$\frac{\partial v_D}{\partial I_D} = \frac{(\rho+I^*)\left(\frac{v_C}{\lambda} - v_I\right)}{(\rho+I^*+I_D)^2} \tag{C.6}$$

and, by (C.4), this is less than zero and the $\beta$-industry leader will not innovate.

C.1.3 Proof that a Previous State-of-the-Art Quality Producer Does Not Have an Incentive to Engage in Innovative R&D in an $\alpha$ Industry

An $\alpha$ industry is being targeted for imitation at $C^*$ intensity in the steady state. But, if a previous state-of-the-art quality producer innovates before imitation occurs, she can earn $\pi_L$ until imitated. But, the current leader has a greater incentive to imitate than the outside fringe since it can then collude with the new quality leader and each can earn $\pi_D/2$. So net benefits to the previous state-of-the-art producer are

$$v_D \qquad \frac{u_I^{\cdot} I_D + I_D v_{CC}}{\rho + C^* + I_D} \tag{C.7}$$

where $v_{CC}$ is defined in (C.3). (C.7) will be less than zero if $\frac{v_I^{\cdot}}{v_C^{\cdot}} > 1 + \frac{1}{\lambda}$, a minor modification of (R1) in the text which is satisfied by the example given in the text. This restriction guarantees that the effect on $v_D$ of the shorter expected period of monopoly profits outweighs the effect of higher collusive profits. Under this condition, innovative activity by a previous state-of-the-art leader can be ruled out.

C.1.4 Proof that a Previous State-of-the-Art Quality Leader Will Have No Incentive to Innovate in a $\beta$ Industry

If this firm innovates it earns $\pi_L$ until imitated and then $\pi_C$ until further innovation. It's situation is exactly analogous to a competition fringe firm which innovates in a $\beta$ industry. Its payoff is

$$v_D \qquad \frac{u_I^{\cdot} I^D + I^D \left( \frac{\pi^L + C^* u_C^{\cdot}}{\rho + C^*} \right)}{\rho + I^D} \qquad 0 \tag{C.8}$$

by (2.15). So this firm has nothing to gain by engaging in innovative activity.

C.1.5 Proof that a Competitive Fringe Firm Will Not Engage in Innovative Activity in an $\alpha$ Industry

This firm will earn $\pi_L$, if it innovates, until imitation occurs. Since $\pi_D /2 >$

$\pi_L/2$. the previous quality leader will have a greater incentive to imitate and (C.7) is this innovating firm's relevant payoff so competition fringe firms have no incentive to engage in innovation in an $\alpha$ industry under the condition discussed there which guarantees that $v_D$ in (C.7) is less than zero.

It has been shown that no firms have any incentive to innovate other than that group of competitive outside firms which enter into the innovative R&D races in each $\beta$ industry until expected discounted profits from innovation are driven to zero. Since (2.3) and (2.4) hold in the steady state. the consumer is maximizing utility and has no incentive to deviate from the equilibrium. F. in Figure 2.1. Quality leaders in all industries are maximizing profits by charging $p = \lambda$ and so have no incentive to deviate from the steady-state equilibrium by charging a different price. That innovation and imitation are symmetric is intuitive since parameters are identical in all industries. That innovation and imitation are constant is implied by the fact that prices. and hence. profits. are constant across time. All firms participating in R&D races are indifferent to doing so since expected discounted profits are always zero. Thus. F in Figure 2.1 is a Nash equilibrium.

## C.2 Chapter 3

In Chapter 2. unit costs. $u_I$ and $u_C$. are determined at the economy-wide level. In Chapter 3. unit costs are determined at the industry level. This changes the method of proof that only outside firms innovate. There are two types of firms which may

consider innovation in an $\alpha$-industry--the current leader or a firm not presently producing (either a firm entirely new to the industry or a previous quality leader).

C.2.1 Proof that Quality Leaders in $\alpha$ Industries Won't Engage in Innovative R&D

Consider the current leader in an $\alpha$-industry. Denote unit costs faced by this dominant firm as $u_{ID}$ and the intensity at which it innovates as $I_D$. If the monopolist innovates, it can charge $p_D = \lambda^2$ and earn $\pi_D = \left(1-\frac{1}{\lambda^2}\right)E$ until imitated, as before. But, since $\pi_D/2 > \pi_C$, $C_D > C^*$ such that $u_{CC} = v_{CC} = (\pi_D/2) / (\rho + I^*)$. That is, this firm, if it successfully innovates, will be imitated more intensely than other industries. The expected net benefits from further innovation are

$$v_D = \frac{-u_{ID} I_D + (\rho + C^*) u_I^* + v_{DD}}{\rho + I_D + C^*} \quad , \tag{C.9}$$

where

$$v_{DD} = \frac{\pi_D + C_D v_{CC}}{\rho + C_D} < \frac{\lambda + 1}{\lambda} v_I^* \quad , \tag{C.10}$$

since $C_D > C^*$ ($v_{CC}$ is defined in (C.3)). Then,

$$\frac{\partial v_D}{\partial I_D} = \frac{(v_{DD} - u_{ID} - u_I^*)(\rho + C^*)}{(\rho + I_D + C^*)} \quad , \tag{C.11}$$

(since the monopolist takes $u_{ID}$ as given - discussed below) and the monopolist will not conduct any R&D if

$$v_{DD} - u_{ID} < u_I^* - v_I^* \quad . \tag{C.12}$$

The monopolist will take $u_{ID}$ as given because this is a contested market. So, $u_{ID}$ is the unit costs which prevail in an innovation race in an $\alpha$-industry. Innovation in an $\alpha$-industry could also be undertaken by outside firms (firms not presently producing in any industry). It will be shown that the monopolist has less incentive to innovate than

outside firms so that, if these outside firms don't innovate, the current leader won't either.

C.2.2 Proof that a Competitive Fringe Firm Will Not Engage in Innovative Activity in an $\alpha$ Industry

If outside firms conduct an innovation race in an $\alpha$-industry, then the winner earns $\pi_L$ until imitated. The current leader will have more to gain by imitation and will preempt other potential imitators by imitating at $C_m \geq C^*$. I will assume that $C_m = C^*$, i.e., the potential monopolist in imitation is constrained by other potential imitators. So the expected payoff in innovation in an $\alpha$-industry by an outside firm is

$$v_D = \frac{-u_{ID} I_D + v_{CD} I_D}{\rho + C^* + I_D} \quad . \tag{C.13}$$

where

$$v_{CD} = \frac{\pi_L + C^* v_{CC}}{\rho + C^*} \quad . \tag{C.14}$$

For $v_D < 0$, it must be that

$$u_{ID} > v_{CD} \Rightarrow (\rho + C^*) u_{ID} > \left( 2(\rho + I^*) + C^* \frac{\lambda + 1}{\lambda} \right) v_C^* \quad . \tag{C.15}$$

which always holds if (substituting 0 for C on the left-hand side (LHS) of (C.15), $C = 1/b_C$, $I = 1/b_I$ and $v_C = \pi_C/(\rho+I)$ (with $I = 0$) on the right-hand side (RHS) of (C.15) and then for $\pi_C$ and also noting that $\rho > \{1/b_C, 1/b_I\}$ by Assumptions A7 and A8),

$$\rho a_D > 3\frac{(\lambda - 1)}{\lambda} E = 3\frac{(\lambda - 1)}{\lambda} (\lambda(\bar{L} - u_I I \beta + u_C C \alpha)) \quad . \tag{C.16}$$

using the labor constraint. This is satisfied by Assumption A4, so that $v_D < 0$, and outside firms will not innovate. Notice that $a_{ID} > a_I$, by comparison of Assumptions A4 and A5. Assume that the monopolist also faces $a_{ID}$ because the reduction in innovative costs as a result of the innovative process is mostly due to experienced gained.

From (C.10) and (C.14) and noting that $v_{CD} < u_{ID}$ and $C_D \geq C_m = C^*$.

$$v_{DD} \quad v_{CD} < \frac{\frac{1}{\lambda}\pi_L}{\rho + C^*} < v_I^* \quad \frac{\pi_L + C^* v_C}{\rho + C} \quad . \tag{C.17}$$

Then, (C.12) is satisfied and quality leaders will not innovate either.

<u>C.2.3 Proof that Quality Leaders Will Not Innovate in a $\beta$ Industry</u>

It has been shown that innovation will not take place in $\alpha$-industries. Now consider innovation by a quality leader in a $\beta$-industry. A $\beta$-industry is already targeted for imitation by outside firms. A $\beta$-industry leader will not have any extra incentive to innovate unless it can expect higher profits than outside firms from doing so. Since it is price constrained, if it innovates, by the other quality leader, it can only expect to earn $\pi_L$, given in (3.3) until imitated. The other dominate firm can, if it imitates, earn $\pi_D/2$. So, it will devote $C_m$ to imitation to earn $v_{CC}$. Then the innovator, if successful, will earn $v_{CD}$ in (C.14). So, the expected net benefits for the $\beta$-industry leader who innovates is

$$v_D = \frac{\pi_C - u_I^* I_D + I_D v_{CD}}{\rho + I_D + I^*} \quad . \tag{C.18}$$

and

$$\frac{\partial v_D}{\partial I_D} = \frac{(v_{CD} - u_I^* - v_C)(\rho + I^*)}{(\rho + I_D + I^*)^2} < 0 \quad .$$

since $v_{CD} - v_C < v_I^* = u_I^*$. So, it has been shown that no innovative activity occurs in $\alpha$ industries.

<u>C.2.4 Proof that Previous Quality Leaders Will Have No Extra Incentive to Innovate</u>

Consider a previous quality leader who might consider innovating in a $\beta$ industry. This firm, if it innovates, earns $\pi_L$ until imitated and then $\pi_C$ until further innovation

occurs. Its situation is exactly the same as an outside firm which innovates in a $\beta$-industry so that it has nothing extra to gain from innovation and does not need to be considered separately from other outside firms.

It has been shown that innovative activity is carried out by outside firms in $\beta$-industries only. Now, consider imitation. For a firm one quality level down in an $\alpha$-industry to engage in imitation, it must expect higher profits than those firms which are already engaged in imitation at $C^*$ such that $u_C^* = v_C^*$. Since there are two followers, if one successfully imitates, it cannot gain more by collusion with the leader than outside firms. So these firms have no extra incentive to imitate.

It has been shown in this section that only outside firms will conduct innovation and no firms will have an incentive to deviate from the Nash equilibrium at F in Figure 3.1 .

APPENDIX D
PROPERTIES OF REDUCED FORMS

## D.1 Chapter 2

It is clear that, in the short run, $K_I$ and $K_C$ are constant for the representative industries, but, by (2.10) and (2.11), this is with $\alpha$ and $\beta$ constant. This will be true in the neighborhood of the steady state where, as is shown in (2.13), $\alpha = \frac{I^*}{I^*+C^*}$, $\beta = \frac{C^*}{I^*+C^*}$ (* denotes steady-state value). To determine the behavior of $C_L(I)$ and $C_I(I)$, however, $\alpha$ and $\beta$ cannot be held constant. As I rises, $\alpha$ begins to rise and $\beta$ begins to fall by (2.12) and noting that $\dot{\beta}(t) = \dot{\alpha}(t)$. So, $K_I = \bar{K}_I/\beta$ rises with I, but since $I = I(L_I, K_I)$ exhibits CRS, as long as $K_I$ rises proportionally less than I, $L_I$ will rise proportionally more than I and the same argument holds for imitation (C). I am not interested in movement out of the steady state but only along $C_L(I)$ and $C_I(I)$. Each point on these two curves is a potential steady state, so (2.15) always holds. Then, from (2.10) and (2.11),

$$\frac{dK_I}{K_I}/\frac{dI}{I} = \frac{\bar{K}_I}{\beta^2}\frac{d\alpha}{dI}\frac{I\beta}{\bar{K}_I} = \frac{d\beta}{dI}\frac{I}{\beta} = \frac{C}{(I+C)^2}\frac{I(I+C)}{I} = \beta \tag{D.1A}$$

will be less than one along $C_I(I)$ and $C_L(I)$. Also

$$\frac{dK_C}{K_C}/\frac{dC}{C} = \frac{\bar{K}_C}{\alpha^2}\frac{d\alpha}{dC}\frac{C\alpha}{\bar{K}_C} = \frac{C}{\alpha}\frac{d\alpha}{dC} = \frac{I}{(I+C)^2}\frac{C(I+C)}{I} = \alpha \tag{D.1B}$$

will be less than one along $C_L(I)$ and $C_I(I)$. It can be shown that, along $C_L(I)$ and $C_I(I)$,

the following are true: $a_{LI}$, $w_I$ and $u_I$ are positively related to I and go to 0 and $\infty$ with I; $a_{KI}$ is negatively related to I and goes to 0 as I goes to $\infty$ and vice versa; and the same properties hold for imitation.

<u>D.1.1 Properties of $C_L(I)$</u>

Totally differentiating (2.17) with respect to I and C, and rearranging gives

$$\frac{\left(\frac{(\lambda-1)}{2}\left(\frac{IC}{1+C}\left(\frac{\partial a_{LI}}{\partial I}\right) + (a_{LI}+a_{LC})\frac{C^2}{(1+C)^2}\right) + u_C\right)}{\left(\frac{(\lambda-1)}{2}\left(\frac{IC}{1+C}\left(\frac{\partial a_{LC}}{\partial C}\right) + (a_{LI}+a_{LC})\frac{I^2}{(1+C)^2}\right) + (\rho+1)\frac{\partial u_C}{\partial C}\right)} = \frac{dC_L(I)}{dI} < 0 \tag{D.2}$$

since $\partial a_{LI}/\partial I > 0$, $\partial a_{LC}/\partial C > 0$ and $\partial u_C/\partial C > 0$. So, $C_L(I)$ is negatively sloped in (C, I) space.

At I=0, (2.17) reduces to

$$\frac{(\lambda-1)\bar{L}}{2} = \rho\, u_C(C^0) \rightarrow (u_C^0)^{-1}\left(\frac{(\lambda-1)\bar{L}}{2\rho}\right) = C^0 > 0\ . \tag{D.3}$$

So $C_L(I)$ has a positive vertical intercept in (C, I) space. At C=0, (2.17) reduces to

$$\left(\frac{(\lambda-1)}{2}\right)\bar{L} = 0\ . \tag{D.4}$$

So, the behavior of I must be examined. As $I \rightarrow \infty$, $C \rightarrow 0$ is consistent with (D.4) for $u_C$ nonconstant. If $u_C$ is constant, then at $C = 0$, $I = \frac{(\lambda-1)}{2u_C}\bar{L} - \rho$.

<u>D.1.2 Properties of $C_I(I)$</u>

Equation (2.18) can be rewritten as

$$C_I = \frac{\left(\left(2 - \frac{u_I}{u_C}\right)\rho + 2I\right)}{\left(\frac{u_I}{u_C} - 1\right)}\ . \tag{D.5}$$

Notice that $C_I > 0$ if

$$2 > \frac{u_I}{u_C} > 1 \tag{R1}$$

which is similar to Segerstrom's parameter restriction of $a_I > a_C$. Differentiating (2.18) yields

$$\frac{dC_I(I)}{dI} = \frac{(\rho+C)\dfrac{\partial u_I}{\partial I} - 2u_C}{[2(\rho+I)+C]\dfrac{\partial u_C}{\partial C} + u_C - u_I}\,, \tag{D.6}$$

which is positive if

$$\frac{\partial u_C}{\partial C} > \frac{u_I - u_C}{2(\rho+I)+C} \tag{R2}$$

and

$$\frac{\partial u_I}{\partial I} > \frac{2u_C}{(\rho+C)}\,. \tag{R3}$$

By some manipulation and substitution from (2.5), (2.6) and (2.18), (R3) is shown to be equivalent to (2.25) and (R2) is equivalent to (2.26).

As I approaches 0, $u_I$ approaches 0. Since the LHS of (2.18) approaches 0 as I approaches 0 this implies that the RHS approaches 0. This means that C must go to 0 as I approaches 0 so that $u_C$ approaches 0 along (2.18). Rewriting (2.18) as

$$\frac{(\rho+C)}{(\rho+I)} = 2\frac{u_C}{u_I} + \frac{C}{(\rho+I)}\frac{u_C}{u_I}$$

shows that $\lim_{I\to\infty} C$ is indeterminant but, if (D.6) > 0, then it will not approach 0. For different specifications, C may approach $\infty$ or a positive constant.

D.1.3 Intercept Terms for Figures 2.2 and 2.3

In Figure 2.2, with $u_C = a_C$, $u_I = a_I$ and assuming $a_I > a_C$ and $\frac{2a_I\rho}{\lambda-1} > \bar{L} > \max\left(\frac{a_I\rho}{\lambda-1}, \frac{2a_C\rho}{\lambda-1}\right)$, $I_3 > I_2 > I_1$ and $C_2 > C_1 > 0$. These terms are

$$I_1 = \frac{\left[\bar{L} - \frac{2a_C\rho}{(\lambda-1)}\right]}{\left[a_I + a_C + \frac{2a_C}{(\lambda-1)}\right]}, \quad I_2 = \frac{\left[\bar{L} - \left(\frac{a_I\rho}{(\lambda-1)}\right)\right]}{\left[\frac{\lambda}{(\lambda-1)}a_I\right]}, \quad I_3 = \frac{(\lambda-1)\bar{L}}{2a_C} - \rho$$

$$C_1 = \frac{[(\lambda-1)\bar{L} - a_I\rho]}{[\lambda a_I + (\lambda-1)a_C]}, \quad C_2 = \frac{(\lambda-1)\bar{L} - a_I\rho)}{\left(a_I - \frac{(\lambda-1)\bar{L}}{2\rho}\right)}$$

In Figure 2.3,

$$C_0 = \sqrt{\frac{(\lambda-1)\bar{L}}{2a_C\rho}}, \quad I_0 = \sqrt{\frac{(\lambda-1)\bar{L}}{\rho a_I}}.$$

## D.2 Chapter 3

### D.2.1 Characteristics of $\dot{I} = 0$

Differentiating (3.16) (with $u_I$, $u_C$ representing unit costs and unit labor requirements for innovation and imitation, respectively),

$$\left.\frac{dC}{dI}\right|_{\dot{I}=0} = -\frac{\left(\frac{\lambda-1}{2}\left(\frac{IC}{I+C}\frac{\partial u_I}{\partial I} + (u_I + u_C)\frac{C^2}{(I+C)^2}\right) + \frac{\partial u_I}{\partial I}\frac{\rho+C}{2}\right)}{\left(\frac{\lambda-1}{2}\left(\frac{IC}{I+C}\frac{\partial u_C}{\partial C} + (u_I + u_C)\frac{I^2}{(I+C)^2}\right) + \frac{u_I(\rho+2I)(\rho+I)}{(2(\rho+I)+C)^2}\right)}, \tag{D.7}$$

which is less than zero so $\dot{I} = 0$ is negatively sloped. At $I = 0$, along $\dot{I} = 0$,

$$\frac{(\lambda-1)\bar{L}}{2} = \frac{\rho(\rho+C)a_I}{2\rho+C}$$

so that, in Figure 3.1,

$$C_0 = \frac{\rho(\rho a_I - (\lambda-1)\bar{L})}{\left(\frac{(\lambda-1)\bar{L}}{2} - \rho a_I\right)} > 0 \tag{D.8}$$

by Assumption A5. At $C = 0$, along $\dot{I} = 0$, $\frac{(\lambda-1)\bar{L}}{2} = u_I$. When $u_I$ is as in (3.6),

$$I_0 = \frac{(\lambda - 1)\bar{L} - \rho a_I}{b_I(\lambda - 1)\bar{L}} > 0 \tag{D.9}$$

by Assumption A5, in Figure 3.1.

D.2.2 Characteristics of $\dot{C} = 0$

Differentiating (3.17),

$$\left.\frac{dC}{dI}\right|_{\dot{C}=0} = -\frac{\left(\frac{(\lambda-1)}{2}\left(\frac{IC}{I+C}\frac{\partial u_I}{\partial I} + (u_I + u_C)\frac{C^2}{(I+C)^2}\right) + u_C\right)}{\left(\frac{(\lambda-1)}{2}\left(\frac{IC}{I+C}\frac{\partial u_C}{\partial C} + (u_I + u_C)\frac{I^2}{(I+C)^2}\right) - (\rho+1)\frac{\partial u_C}{\partial C}\right)} \quad , \tag{D.10}$$

which is less than zero so that $\dot{C} = 0$ is negatively sloped in the positive quadrant. At $I = 0$, along $\dot{C} = 0$, in Figure 3.1, by Assumptions A5 and A6,

$$C_1 = \frac{\frac{(\lambda-1)\bar{L}}{2} - a_C\rho}{b_C\frac{(\lambda-1)\bar{L}}{2}} > 0 \quad . \tag{D.11}$$

At $C = 0$, along $\dot{C} = 0$, by Assumptions A5 and A6,

$$I_1 = \frac{(\lambda-1)\bar{L}}{2a_C} - \rho > 0 \quad . \tag{D.12}$$

D.2.3 Comparison of $C_0$ and $C_1$

$C_0 > C_1$ if, using Assumption A6 and rearranging,

$$(2\rho b_C + 1)(\lambda - 1)\bar{L} > 2\rho a_I \quad . \tag{D.13}$$

Using Assumption A5, (D.12) is true if $(2\rho b_C + 1) > 2$, which is true by Assumption A8. So,

$$C_0 > C_1 \; .$$

Also, by Assumptions A5, A6, and A7,

$$I_1 > I_0 \, .$$

So, $\dot{I} = 0$ and $\dot{C} = 0$, under these conditions, can be graphed as in Figure 3.1 so that an equilibrium, F, exists.

<u>D.2.4 Characteristics of $C_{ZPC}(I)$</u>

To show that F is unique in the positive quadrant, examine (3.16) and (3.17). The equations $\dot{I} = 0$ and $\dot{C} = 0$ can intersect only where (3.18) holds. Substituting into (R2) from (3.6) and (3.8), and rearranging,

$$b_I > \frac{2}{(2(\rho+1)+C)+2I} \quad .$$

which always holds under Assumption A7. Using (3.18) and (R3)

$$\frac{\partial u_C}{\partial C} > \frac{u_C}{(\rho+C)} \frac{(\rho+2I)}{(2(\rho+1)+C)} \quad .$$

Noting that the second term is a fraction, using (3.8) and some manipulation, (R3) holds if $b_C > \dfrac{1}{\rho+2C}$ , which is always satisfied, by Assumption A8. $C_{ZPC}(I)$ is positively sloped. At $I = 0$, along $C_{ZPC}(I)$,

$$C_{ZPC} \quad \frac{\left(2 \quad \frac{a_I}{u_C}\right)\rho}{\left(\frac{a_I}{u_C} \quad 1\right)} \quad .$$

which is satisfied by $C_{ZPC} = 0$ when Assumption A7 holds. Note that, as $I \rightarrow 1/b_C$ along $C_{ZPC}(I)$, $C \rightarrow 1/b_C$.

So $C_{ZPC}(I)$ is a positively sloped function in the positive quadrant of (C,I) space and so can intersect $\dot{I} = 0$ and $\dot{C} = 0$ at most once. Since $C_0 < 1/b_C$ SUPRA $C_{ZPC}$ , there is at least 1 intersection with $C_{ZPC}(I)$ for both $\dot{I} = 0$ and $\dot{C} = 0$. This must be at F in Figure 3.1. F exists and is unique.

## APPENDIX E
## DERIVATION OF PHASE DIAGRAMS

From (2.19), $\dot{I}(t) > 0$ if $v_I > u_I$ or LHS of (2.21) > RHS of (2.21). Now

$$\frac{dLHS}{dI} = -\left(\frac{\lambda-1}{2}\right)\left[\frac{C^2}{(I+C)^2}(u_I+u_C)+\frac{IC}{I+C}\frac{\partial u_I}{\partial I}\right] < 0 \tag{E.1}$$

and

$$\frac{dRHS}{dI} = \frac{(\rho+I)(\rho+C)\frac{\partial u_I}{\partial I} - u_C C}{(2(\rho+I)+C)} > 0 \tag{E.2}$$

for $\theta \geq 0$, $\phi \geq 0$. (At $\theta$, $\phi = 0$, $u_I$, $u_C$ are constant, and $\frac{\partial u_I}{\partial I}=0$). Starting from a point on $\dot{I} = 0$, and for given C, a lower I implies LHS (2.21) > RHS (2.21) $\Rightarrow v_I > u_I \Rightarrow \dot{I}(t) > 0$. Similarly, a higher I implies $\dot{I}(t) < 0$.

From (2.20), $\dot{C}(t) > 0$ if $v_C > u_C$ or, for given I, LHS of (2.22) > RHS of (2.22). Now

$$\frac{dLHS}{dC} = -\left(\frac{\lambda-1}{2}\right)\left[\frac{I^2}{(I+C)^2}(u_I+u_C)+\frac{IC}{I+C}\frac{\partial u_C}{\partial C}\right] < 0 \tag{E.3}$$

and

$$\frac{dRHS}{dC} = \frac{\partial u_C}{\partial C}(\rho+I) \geq 0 \tag{E.4}$$

for $\theta \geq 0$, $\phi \geq 0$. Starting from a point on $\dot{C}(t) = 0$, for a given I, a lower C implies LHS (2.22) > RHS (2.22) $\Rightarrow v_C > u_C \Rightarrow \dot{C}(t) > 0$. Similarly, a higher C implies $\dot{C}(t) < 0$. This information implies the arrows of motion in Figures 2.2, 2.3, and 3.1.

As pictured, with $\dot{I} = 0$ steeper than $\dot{C} = 0$, F is stable in Figures 2.3 and 3.1. To

ensure that the absolute value of the slope of $\dot{I} = 0$ is greater than the absolute value of the slope of $\dot{C} = 0$, or

$$\left| \left. \frac{dC}{dI} \right|_{\dot{I}=0} \right| > \left| \left. \frac{dC}{dI} \right|_{\dot{C}=0} \right| , \tag{E.5}$$

This is assured by (SC1) and (SC2), in Chapter 2, and Assumptions 7 and 8, in Chapter 3. So, a unique, stable steady-state equilibrium exists at F in Figures 2.3 and 3.1.

## APPENDIX F
## COMPARATIVE STATICS
## (Chapters 2 and 3)

### F.1 Subsidy to Innovation

Suppose the government wants to give a general per-unit specific subsidy to innovative R&D activity and finances it by lump sum taxes on consumers. Then the effect of the taxes can be ignored since there are no substitution effects. The effect of a government subsidy to innovation is to change (2.15) to

$$v_I = u_I - s_I . \tag{F.1}$$

Then (2.22) is unaffected but (2.21) becomes

$$\frac{(\lambda-1)}{2}\left(\bar{L} - \frac{IC}{I+C}(\epsilon a_I I^{\theta} + \gamma a_C C^{\phi})\right) = \frac{(a_I I^{\theta} - s_I)(\rho+I)(\rho+C)}{2(\rho+I)+C} , \tag{F.2}$$

for which

$$\left.\frac{\partial C(I,s_I)}{\partial s_I}\right|_{\dot{I}=0,\ s_I=0} = \frac{\dfrac{(\rho+I)(\rho+C)}{2(\rho+I)+C}}{\left(\dfrac{\lambda-1)}{2}\left(\left(\dfrac{IC}{I+C}\right)(\phi\gamma a_C C^{\phi-1}) + \dfrac{I^2}{(I+C)^2}(\epsilon a_I I^{\theta} + \gamma a_C C^{\phi})\right) + \dfrac{a_I I^{\theta}(\rho+I)(\rho+2I)}{(2(\rho+I)+C)^2}\right)}$$

is less than zero, so that $\dot{I} = 0$ shifts up in Figures 2.2 and 2.3 as suggested in the text. This result is not affected by the functional forms of unit costs and, so, holds for Chapter 3 as well.

## F.1.2 Subsidy to Imitation

Next, consider that the government might want to subsidize imitative R&D. A general per-unit specific subsidy will make (2.12)

$$v_C = u_C - s_C \quad . \tag{F.3}$$

This will not affect (2.21) but (2.22) will become

$$\frac{(\lambda-1)}{2}\left(\bar{L} - \frac{IC}{I+C}(\epsilon a_I I^{\theta} + \gamma a_C C^{\phi})\right) = (a_C C^{\phi} - s_C)(\rho + I) \quad , \tag{F.4}$$

for which

$$\left.\frac{\partial C(I,s_C)}{\partial s_C}\right|_{\dot{C}=0,\ s_C=0} = \frac{(\rho+I)}{\left(\frac{(\lambda-1)}{2}\left(\left(\frac{IC}{I+C}\right)\gamma\phi a_C C^{\phi-1} + \frac{I^2}{(I+C)^2}(\epsilon a_I I^{\theta} + \gamma a_C C^{\phi})\right) + \phi a_C C^{\phi-1}(\rho+I)\right)}$$

is less than zero, so that $\dot{C}$ shifts up in Figures 2.2 and 2.3 as suggested in the text. Again, this result also applies for Chapter 3.

# APPENDIX G
# WELFARE ANALYSIS

## G.1 Derivation of the Growth Rate of Instantaneous Utility

Substituting p = λ and static demand into u(t) gives:

$$u(t) = \int_0^1 \ln\left[\lambda^h(\omega)\frac{E}{\lambda}\right]d\omega$$
$$= \int_0^1 \ln\lambda^h(\omega)d\omega + \ln E - \ln\lambda \qquad \text{(G.1)}$$

Recall that h is the highest quality available in each industry $\omega$ and only changes when a successful innovation occurs. Innovation occurs in $\beta = C^* / (I^*+C^*)$ industries and the probability of exactly m innovations in each targeted industry in interval $\tau$ is

$$f(m,\tau) = \frac{(I^*\tau)^m e^{-I^*\tau}}{m!} \quad , \qquad \text{(G.2)}$$

where m is the random number of innovations in $\tau$, $I\tau$ is the mean occurrence and f is the Poisson density function. Then the expected number of industries which are improved in $\tau$ exactly m times is $\beta$ f $(m,\tau)$. Assuming that at t=0, h=0, the value of

$$\int_0^1 \ln\lambda^h dw \qquad \text{(G.3)}$$

at each t can be calculating by multiplying the expected number of industries with m improvements at t, relative to t=0, by $\ln\lambda^m$, the value of m improvements, and summing across all possible values of m. So,

$$\int_0^1 \ln\lambda^h dw = \sum_{m=o}^{\infty} \beta f(m,t)\ln\lambda^m$$

$$= \beta\ln\lambda \sum_{m=0}^{\infty} f(m,t)m = \beta I^* t\ln\lambda = \frac{I^* C^* \ln\lambda t}{I^* + C^*} \tag{G.4}$$

Then the steady-state growth of expected utility is

$$g^* = \frac{du(t)}{dt} = \frac{I^* C^* \ln\lambda}{I^* + C^*} .$$

This is equation 3.19 in the text.

## G.2 Derivation of Welfare

By substituting from (G.1) and (G.5) into the utility function,

$$U = \int_0^{\infty} e^{-\rho t}\left[\ln\frac{E}{\lambda} + \beta I t\ln\lambda\right]dt \tag{G.5}$$

Letting $x = \left[\ln\frac{E}{\lambda} + \beta I t\ln\lambda\right]$, $dy = e^{-\rho t}dt$, and integrating by parts gives (2.20).

## G.3 Welfare Properties of the World Economy

To find the welfare maximizing level of I, C, ($I^m$, $C^m$), substitute into (3.20) from (3.9) and (3.19) to get

$$U = \frac{1}{\rho}\left[\ln\left(L - \frac{IC}{I+C}(u_I + u_C)\right) + \frac{1}{\rho}\left(\frac{IC\ln\lambda}{I+C}\right)\right] \quad . \tag{G.6}$$

The F.O.C. are

$$\frac{\partial U}{\partial I} = \frac{1}{\rho}\left[\frac{-\left(\frac{C^2}{(I+C)^2}(u_I+u_C) + \frac{IC}{I+C}\frac{\partial u_I}{\partial I}\right)}{\left(\bar{L} - \frac{IC}{I+C}(u_I+u_C)\right)} + \frac{\ln\lambda}{\rho}\frac{C^2}{(I+C)^2}\right] = 0 \tag{G.7}$$

and

$$\frac{\partial U}{\partial I} = \frac{1}{\rho}\left[\frac{-\left(\frac{I^2}{(I+C)^2}(u_I+u_C) + \frac{IC}{I+C}\frac{\partial u_C}{\partial C}\right)}{\left(\bar{L} - \frac{IC}{I+C}(u_I+u_C)\right)} + \frac{\ln\lambda}{\rho}\frac{I^2}{(I+C)^2}\right] = 0 \ . \tag{G.8}$$

The S.O.C., $\frac{\partial^2 U}{\partial C^2} < 0$ , $\frac{\partial^2 U}{\partial I^2} < 0$ and $\frac{\partial^2 U}{\partial C^2}\frac{\partial^2 U}{\partial I^2} > \left(\frac{\partial^2 U}{\partial C \partial I}\right)^2$ are assumed satisfied at ($I^m$, $C^m$). By minimal rearrangement, (G.7) and (G.8) can be written as

$$\frac{C^2}{(I+C)^2}(u_I+u_C) + \frac{IC}{I+C}\frac{\partial u_I}{\partial I} = \left(\bar{L} - \frac{IC}{I+C}(u_I+u_C)\right)\frac{\ln\lambda}{\rho}\frac{C^2}{(I+C)^2} \tag{G.7$'$}$$

and

$$\frac{I^2}{(I+C)^2}(u_I+u_C) + \frac{IC}{I+C}\frac{\partial u_C}{\partial C} = \left(\bar{L} - \frac{IC}{I+C}(u_I+u_C)\right)\frac{\ln\lambda}{\rho}\frac{I^2}{(I+C)^2} \quad . \tag{G.8$'$}$$

Dividing (G.7′) by $\frac{C^2}{(I+C)^2}$ and (G.8′) by $\frac{I^2}{(I+C)^2}$ , (G.7′) and (G.8′) together imply that

$$\frac{I}{C}\frac{\partial u_I}{\partial I} = \frac{C}{I}\frac{\partial u_C}{\partial C}$$

or, using (3.6) and (3.8),

$$I^2 u_I \frac{b_I}{1-b_I I} = C^2 u_C \frac{b_C}{1-b_C C} \Rightarrow \left(\frac{u_I}{u_C}\right)^2 = \left(\frac{C}{I}\right)^2 2\frac{b_C}{b_I} ,$$

where the LHS of the first expression is multiplied by $a_I/a_I$ , the RHS by $a_C/a_C$, and Assumption A6, holding with equality, is used to obtain the second expression. Then, using Assumption A8,

$$u_I^m I^m = u_C^m C^m \quad . \tag{G.9}$$

So, the welfare maximizing levels of innovation and imitation in the world economy are positive. This equal expenditure result is due to Assumptions A6 and A8. Equation G.9 is used below for ease of analysis. This result is in contrast to the conclusion of Segerstrom and Davidson (1992) that the optimal level of imitation is zero. In the present version of the model, imitation plays an important role in the diffusion of knowledge which spills over to lower unit costs of subsequent innovation thus contributing to the ongoing growth process. The extreme nature of the assumption implies that if C = 0 then I = 0 since costs are <u>always</u> too high to allow innovation in monopoly industries. Then, utility in this no growth case can be compared to utility when ($I^m$, $C^m$) obtains (from equations 3.19 and 3.20):

$$U_{I=C=0} = \frac{1}{\rho} (\ln\bar{L}) \tag{G.10}$$

and

$$U_m = \frac{1}{\rho}\left[\ln(\bar{L} - u_I^m I^m) + \frac{1}{\rho}\left(\frac{I^m C^m}{I^m + C^m}\ln\lambda\right)\right] . \tag{G.11}$$

[Note: $\beta u_I^m I^m + \alpha u_C^m C^m = u_I^m I^m$ , using (3.11) and (G.9)]. $U_m > U_{I=C=0}$ if

$$\frac{I^m C^m}{I^m + C^m}\frac{\ln\lambda}{\rho} > \ln(u_I^m I^m) \quad . \tag{G.12}$$

From (3.4), (3.9), (3.13), (G.7) and (G.8),

$$\frac{\ln\lambda}{\rho}\frac{C^{m}}{I^{m}+C^{m}}\frac{2(\rho+I^{m})}{\lambda-1}u_C^{m} = u_I^{m}\left(1+\frac{b_I}{a_I}u_I^{m}I^{m}\right) \quad . \tag{G.13}$$

Multiplying through by $I^m$, using (G.9) to cancel terms, using Assumption A3, and noting the terms which are fractions, it is true that

$$\frac{\ln\lambda}{\rho} > \left(1+\frac{b_I}{a_I}u_I^{m}I^{m}\right) \quad .$$

So, (G.16) will hold, by Assumption A7, since $u_I^{m}I^{m} > \ln u_I^{m}I^{m}$ for $I^m > 0$. The welfare maximizing level of imitation is then positive. This result is consistent with that of Dinopoulos (1992) in which imitation is in the form of product differentiation via variety expansion. There, imitation adds directly to utility by expanding variety. Here the role of imitation is in diffusion or spillovers operating on the production side. The result in (G.9) is due to the built-in symmetry of the model but highlights the role of diffusion. Since industries must have experienced some period of diffusion of stochastic length in order to be targeted for innovation in each industry, (G.9) balances the intensity of innovation in each industry against the number of industries targeted for innovation. It seems reasonable to conjecture the possibility that a more moderate assumption concerning diffusion than Assumption A4, which would allow some innovation in $\alpha$-industries, would still result in a positive optimal level of imitation.

APPENDIX H
ENDOWMENT REGIONS

Since everything is symmetric, $\bar{L}_H^M$ and $\bar{L}_H^{MM}$ are derived with the understanding that $\bar{L}_F^M$ and $\bar{L}_F^{MM}$ are analogously defined. Using (3.22) and substituting for $L_{IH}$ and $L_{IC}$ in (3.23) gives

$$\bar{L}_H = (\alpha_H + \beta_H + \bar{\beta}/2)\frac{E}{\lambda} + \beta^* u_I^* I_H + \alpha^* u_C^* C_H \quad . \tag{H.1}$$

Substituting from (3.25), (3.28), (3.4), and (3.13),

$$\bar{L}_H = \left(\frac{I_H}{I^*}\alpha^* + \frac{1}{2}\left(\frac{C_H}{C^*} + \frac{I_H}{I^*}\right)\beta^*\right)\frac{2}{(\lambda-1)}(\rho + I^*)u_C^* + \beta^* u_I^* I_H + \alpha^* u_C^* C_H \quad . \tag{H.2}$$

Taking $I^*$ and $C^*$ as given and directing the RHS of (H.2) as $L_H^D$,

$$M_1 = \frac{\partial L_H^D}{\partial C_H} = \frac{[(\rho + I^*) + (\lambda-1)I^*]u_C^*}{(I^* + C^*)(\lambda-1)} \quad , \tag{H.3}$$

and

$$M_2 = \frac{\partial L_H^D}{\partial I_H} = \frac{[(\rho + I^*)2I^* + C^*(\rho + I^*)]u_C^*}{I^*(I^* + C^*)(\lambda-1)} + \frac{u_I^* C^*}{I^* + C^*} \quad , \tag{H.4}$$

after some manipulation. Since these are independent of $L_{IH}$ and $L_{CH}$, it is clear that there must be some minimum level of labor at Home to engage in R&D and the associated production. Define

$$\bar{L}_H^{M} = \min\{M_1, M_2\}$$

and

$$\bar{L}_H^{MM} = M_1 + M_2 \ .$$

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Elias Dinopoulos, Chairman
Professor of Economics

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Richard Romano

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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